Advancing Our Knowledge of Terrestrial and Space Weather: Reflections on 15+ Years of Research

Dr. Xia Cai

APS Seminar, Hampton University
March 8, 2023

Content

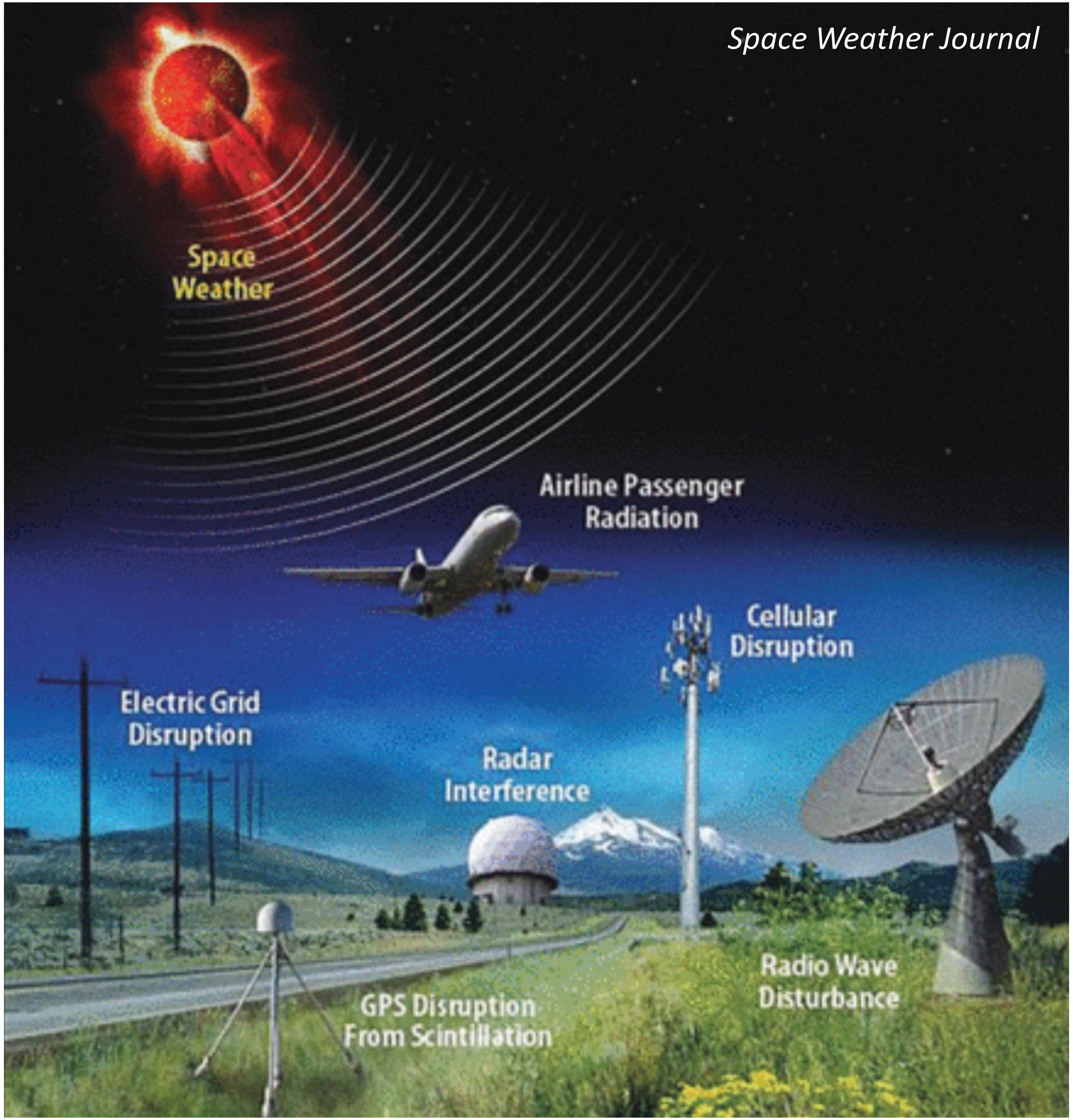
1. Space weather
2. Terrestrial weather
3. Interdisciplinary between space and terrestrial weather

1. Space Weather

Developed a phenomenological model of sawtooth oscillation events; simulated sawtooth oscillation events using a global numerical model.

Fund (total: ~ 1.5 M)

- NSF Geospace environment modeling (GEM) postdoctoral research fellowship, GEM program
- NASA Heliophysics Supporting Research



Space Weather

Space weather refers to the conditions and processes occurring in space that can potentially produce harmful effects on infrastructure, communications, or humans in space or on ground.

CLASP, Umich

NEWS | SpaceX says up to 40 Starlink satellites lost to geomagnetic storm | SHARE & SAVE —

SPACE

SpaceX says up to 40 Starlink satellites lost to geomagnetic storm

The now-defunct satellites are expected to fall back to Earth in the coming days and burn up in the atmosphere.

Why care?

Feb. 9, 2022, 4:08 PM EST / Updated Feb. 9, 2022, 4:22 PM EST

By Denise Chow

Up to 40 Starlink satellites, launched earlier this month as part of Elon Musk's efforts to build a high-speed internet network, were lost after a recent geomagnetic storm in space, company officials confirmed Tuesday.

$ 50 million loss

US, Thailand kick off Cobra Gold 2023 military exercises

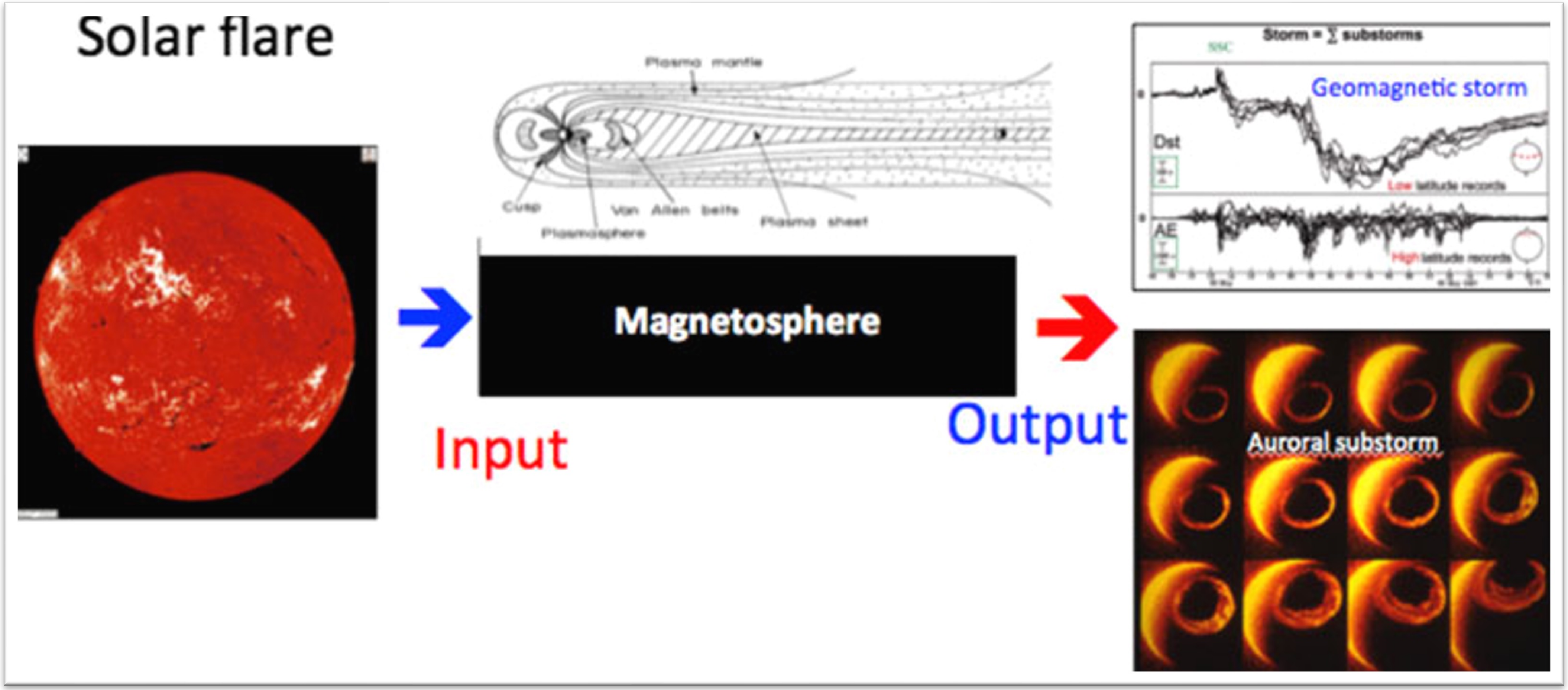
Nontarat Phaicharoen
2023.02.28
Rayong, Thailand

Service members display flags of participating nations during the Cobra Gold 2023 opening ceremony at U-Tapao Air Base in Rayong province, Thailand, Feb. 28, 2023.

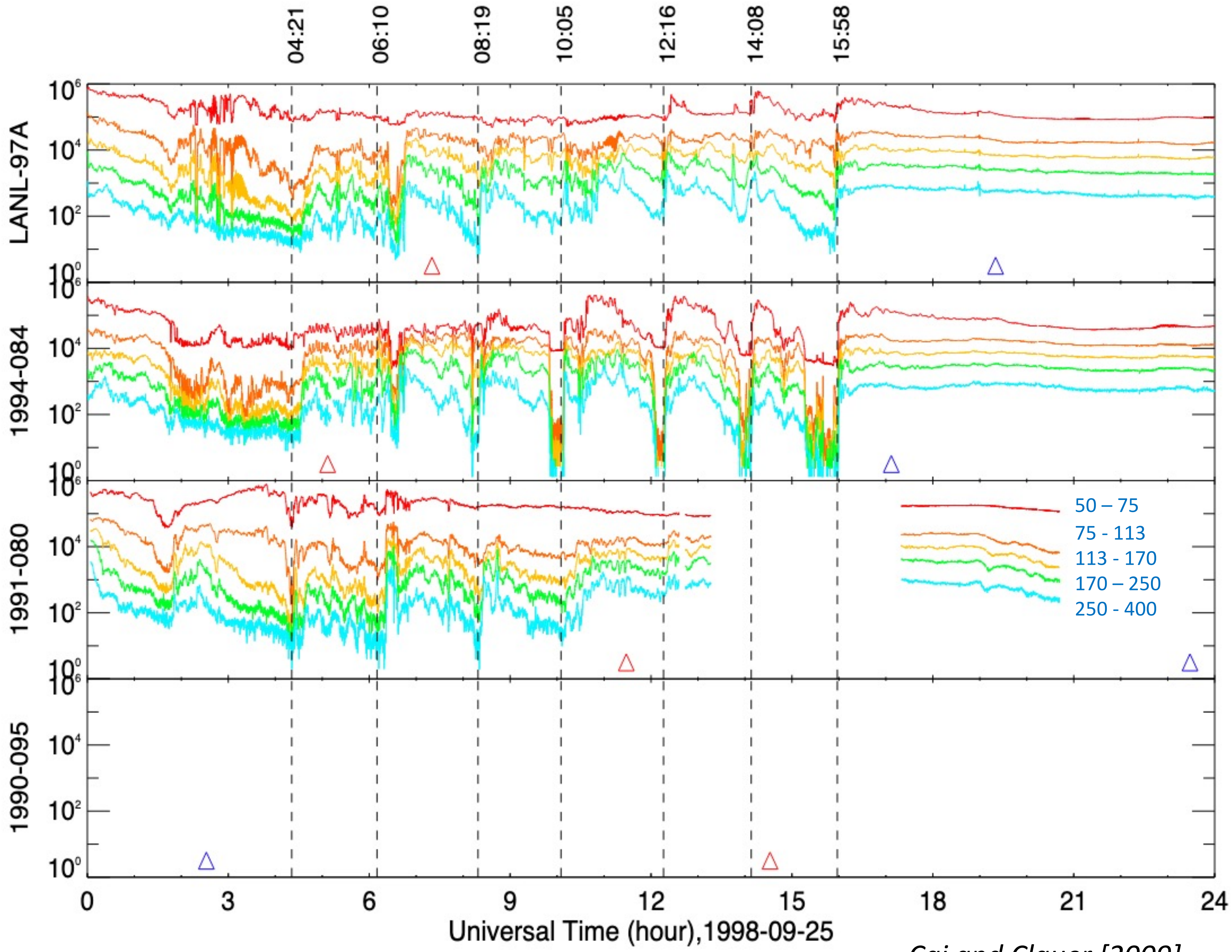
A space exercise focusing on how solar storms and other phenomena can affect military operations will be held for the first time, a U.S. embassy statement said.

Different Space Weather

Magnetic storms, substorms, steady magnetospheric convections, sawtooth oscillations…



Akosofu [2021]



Cai and Clauer [2009]

Sawtooth events

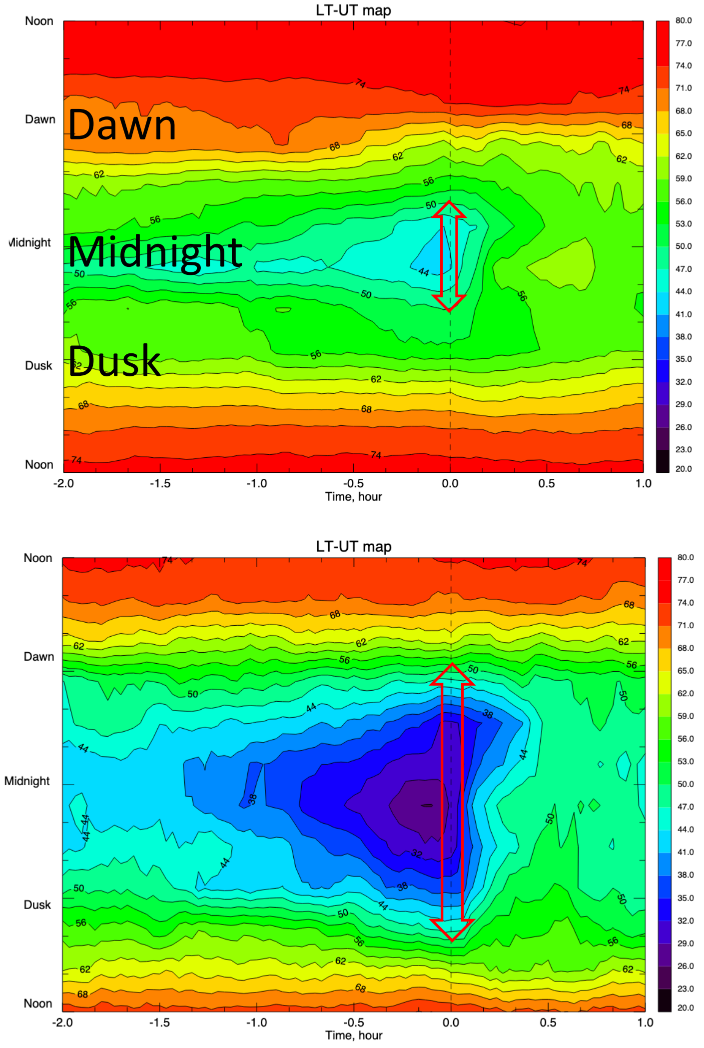
- Defined by proton flux (50 keV – 400 keV) at geosynchronous orbit
- Quasi-periodic (179.6 +/- 54 min)
- Large local time extent (12 hour or 180°)

Phenomenological model of sawtooth events

At 6.6 R_E

Substorm

Sawtooth

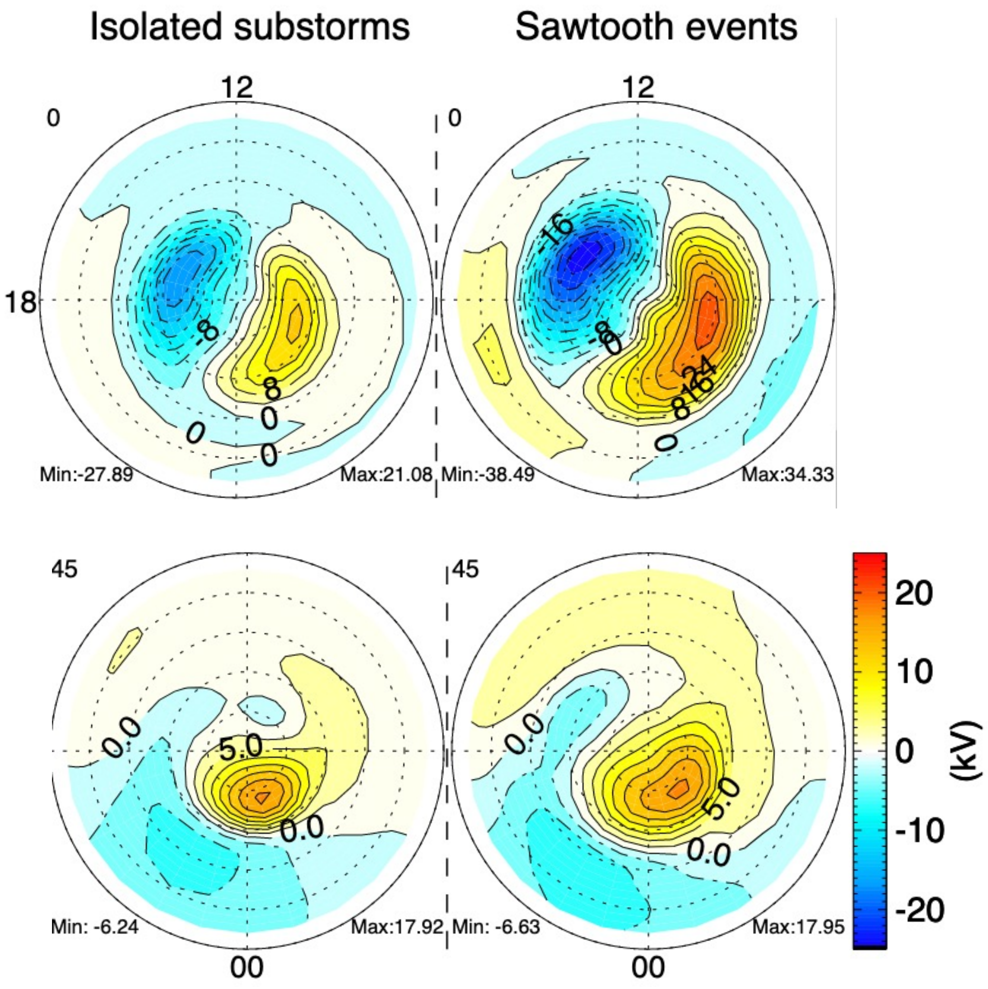


The magnetic tilt angle, $0^o \rightarrow$ tail-like, $90^o \rightarrow$ dipolar-like

At ionosphere

Twin vortex current

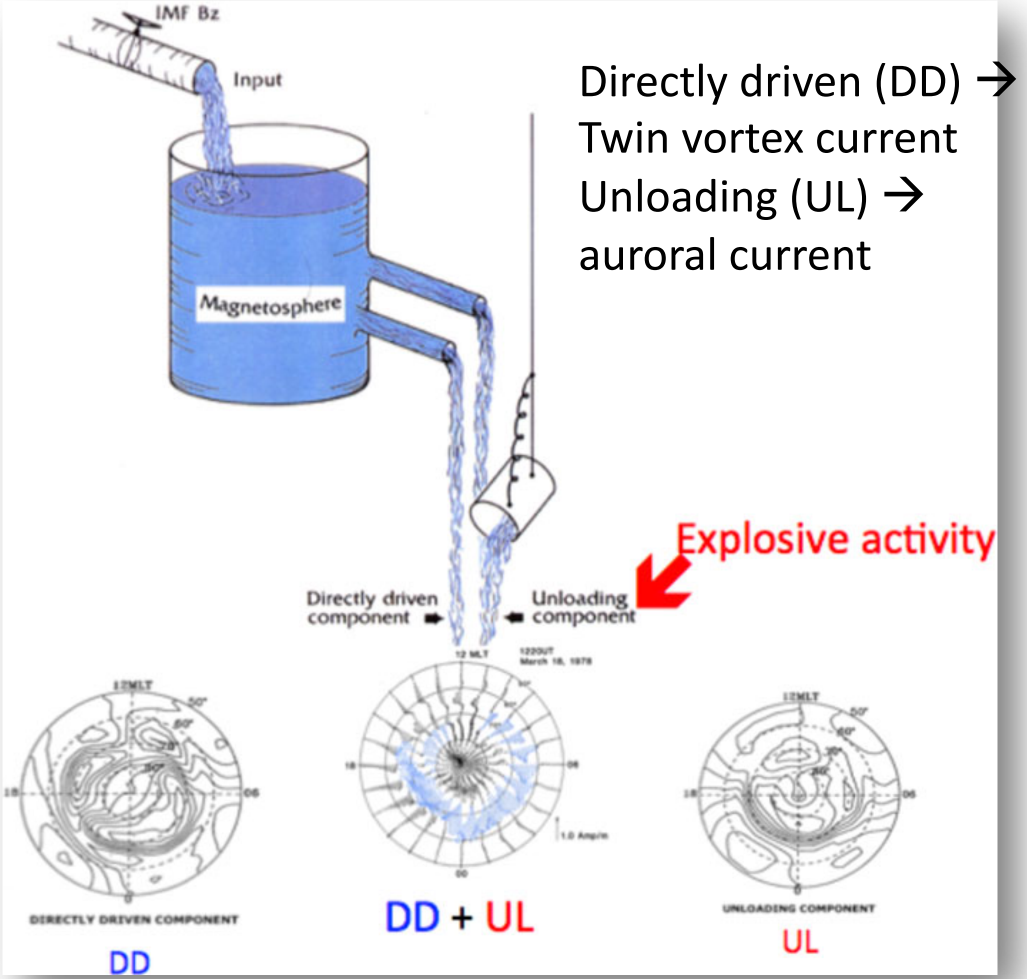
Auroral current



Electric potential patterns

Cai et al. [2006a, 2006b]

Why sawtooth?

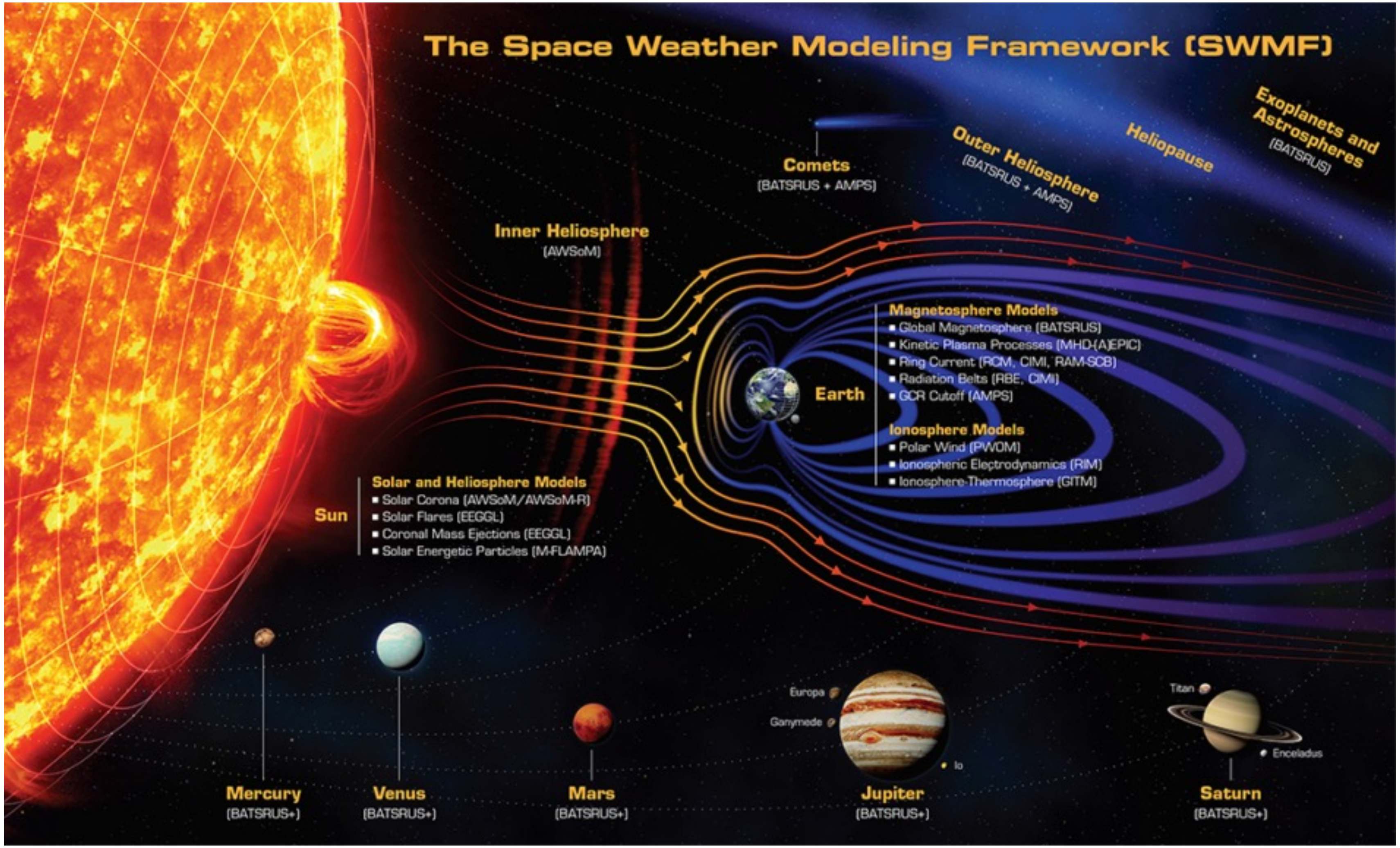


The tank-tippy pitcher model

Akasofu [2021]

- What causes periodic unloading?
- Hypothesis: a long duration of strong southward interplanetary magnetic field
- How to test? Controlled numerical experiments using a global magnetosphere model.

Numerical experiments



Different solar drivers:

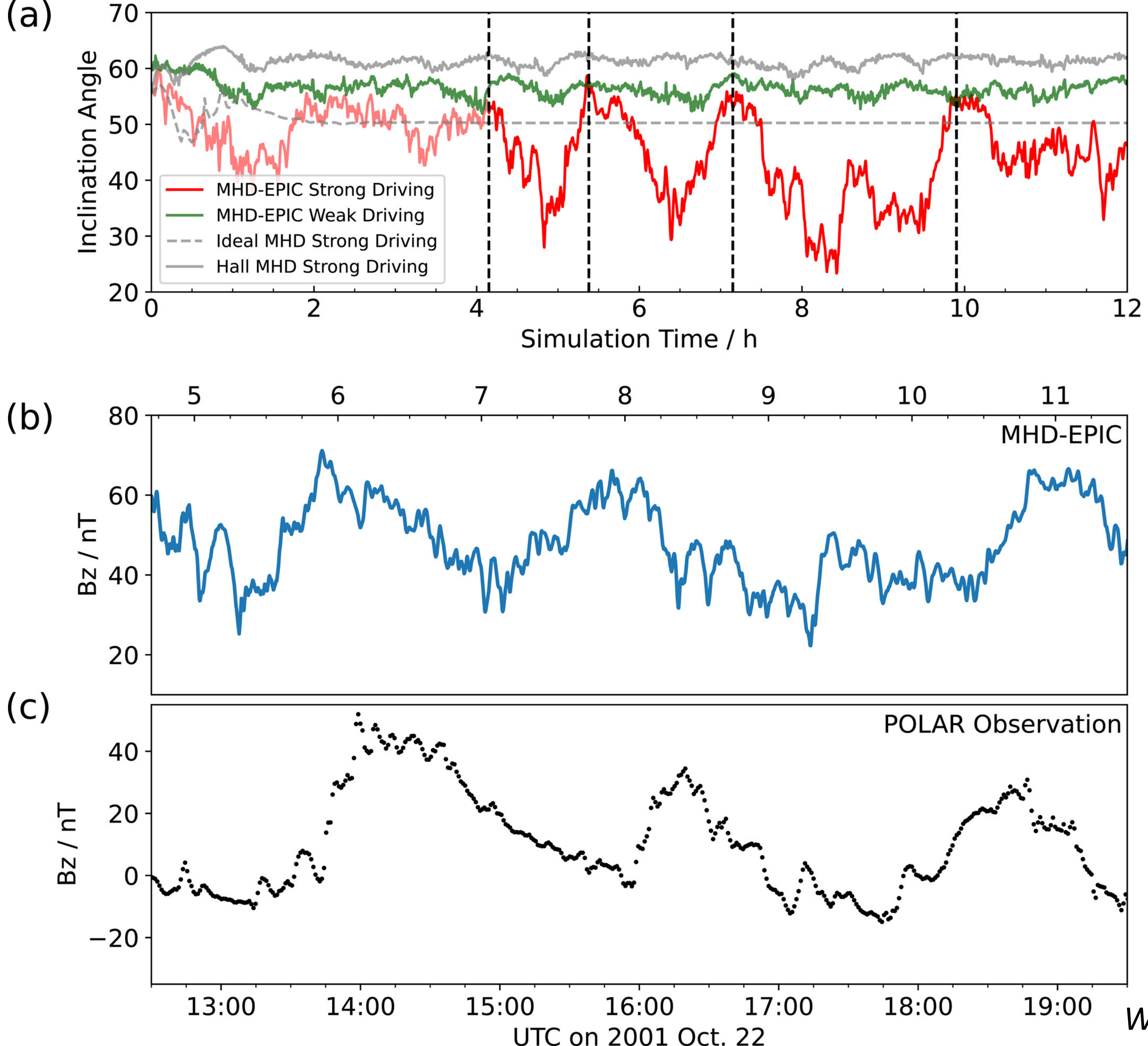
- Strong (Bz = -15 nT)
- Weak (Bz = -5 nT)

Different “flavors”

- Ideal MHD
- Hall MHD
- MHD + kinetic in PIC

Note: no internal contribution from ionospheric outflow

Wang et al. [2022]



Sawtooth events are seen during

- Strong solar driver
- MHD + kinetic in PIC

Wang et al. [2022]

Where to go from here?

- <u>How to define sawtooth events using other datasets?</u>
  - Limited LANL data access after 2008. Ground magnetometer data could be a solution.

- <u>How to predict sawtooth events based on solar wind conditions?</u>
  - A statistical study of solar wind condition.

- <u>Numerical modeling:</u>
  - Ionosphere contribution?

- <u>Funding opportunities:</u>
  - NSF GEM, NASA Heliophysics Supporting Research, NASA Heliophysics Guest Investigator, NASA Living with Star

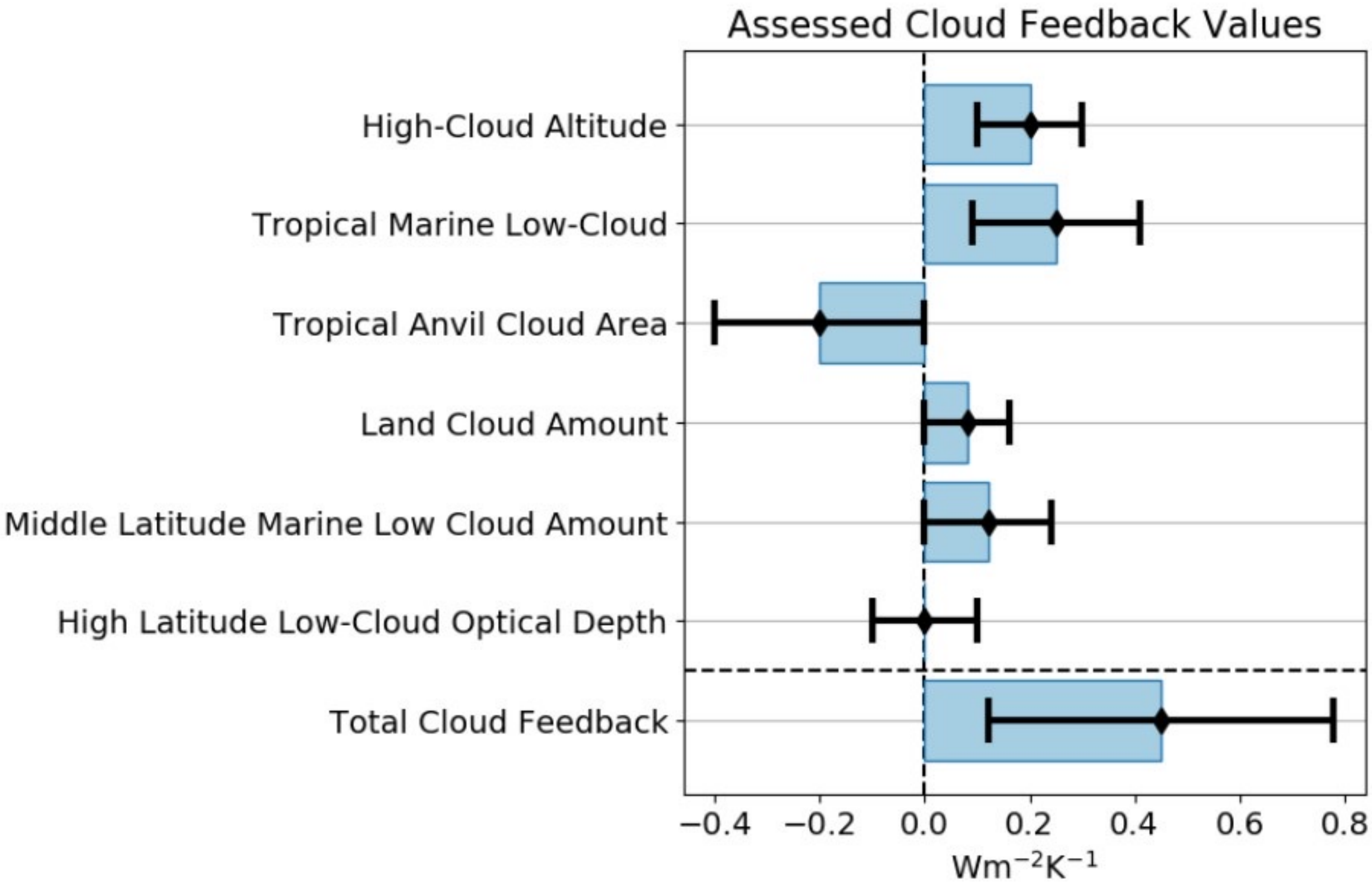
2. Terrestrial Weather

- Team member of NASA CALIPSO mission
- Team member of NASA Instrument Incubator Program: Microwave Barometric Radar and Sounder
- Co-I of NASA IRAD and LaRC SPIN seed fund to demonstrate a concept of next generation of atmospheric water observatory using Starlink constellation

Weather forecast and climate prediction is crucial for everyday life

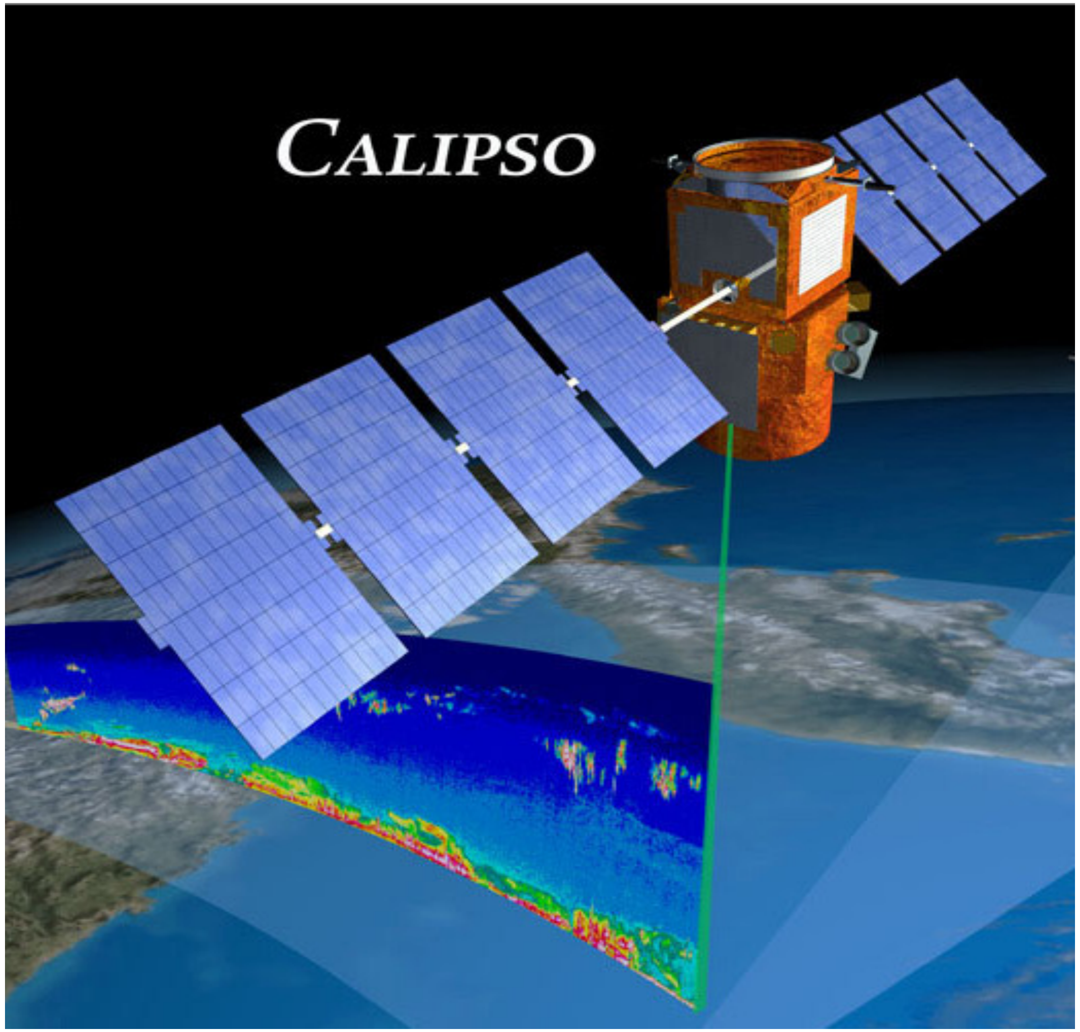
MetOffice(UK)

Cloud feedbacks have large uncertainty of climate sensitivity



Information on cloud fraction, height, phase, and optical depth is important.

CALIPSO measures profiling of clouds and aerosols from space

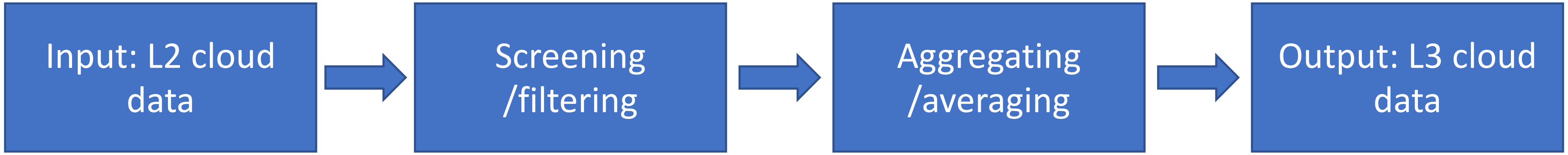


- ~ 17 years of success (June 2006 – current)
- Precisely determine the altitudes of clouds and aerosols
- Extremely high sensitivity → detect very thin cirrus clouds
- Accurately determine cloud phase
- Operates day and night
- Global coverage, -82^o S – 82^o N

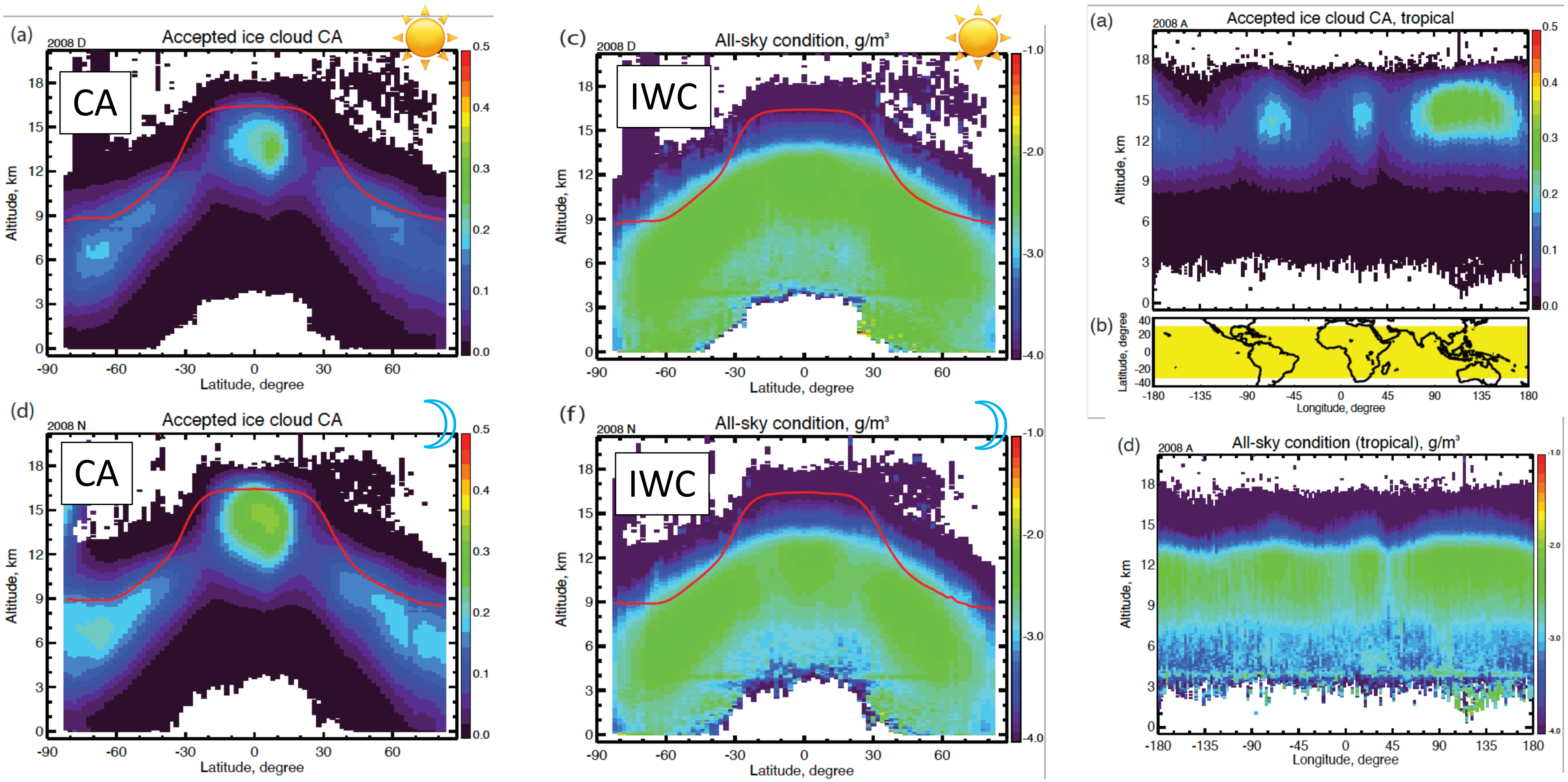
Level 3 cloud climatology

- NASA defines level 3 data products containing ”variables mapped on uniform space-time grid scales, usually with some completeness and consistency”. Level 3A data “are generally period summaries (weekly, ten-day, monthly)”

- Led the development of three Level 3 cloud products:
  - **Ice cloud product** – histograms of ice cloud extinction coefficients and ice water content
  - **3-dimenstioanl cloud occurrence product** – count of cloud samples and ice cloud optical depth histogram
  - **GEWEX cloud product** – support support Global Energy and Water cycle Experiment (*GEWEX*) *Cloud* Assessment



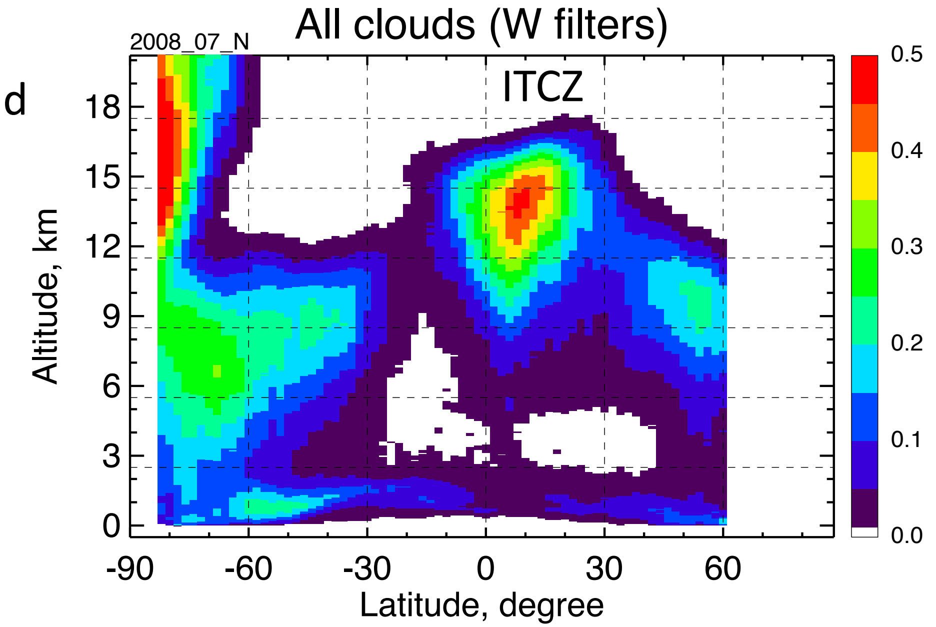
CALIPSO L3 ice cloud product



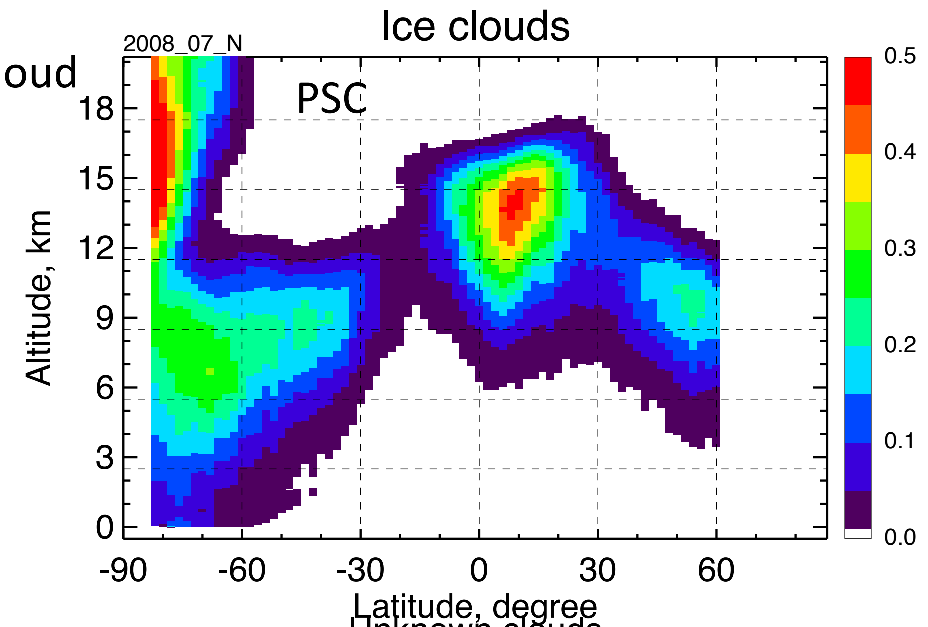
CALIPSO 3D cloud occurrence product

Night, July 2008

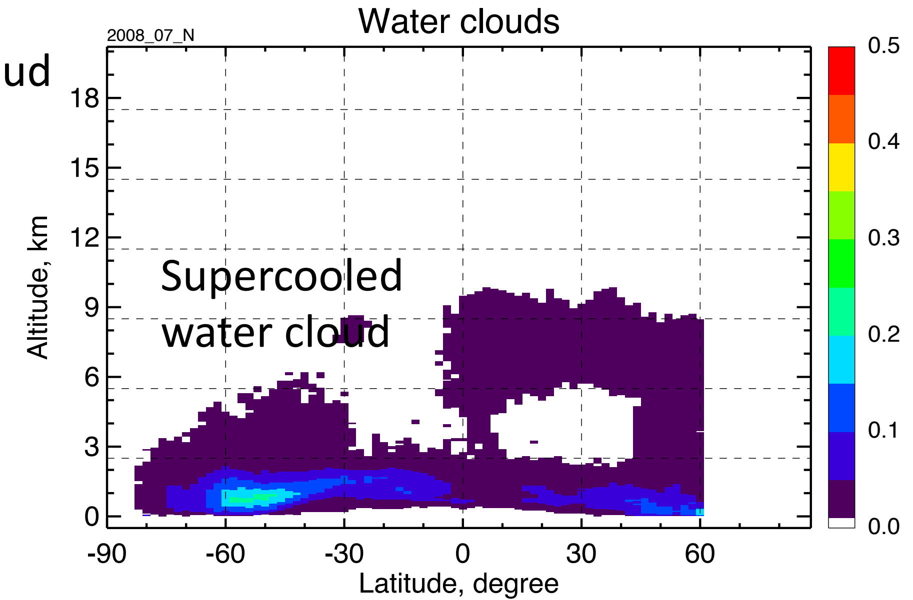
All cloud



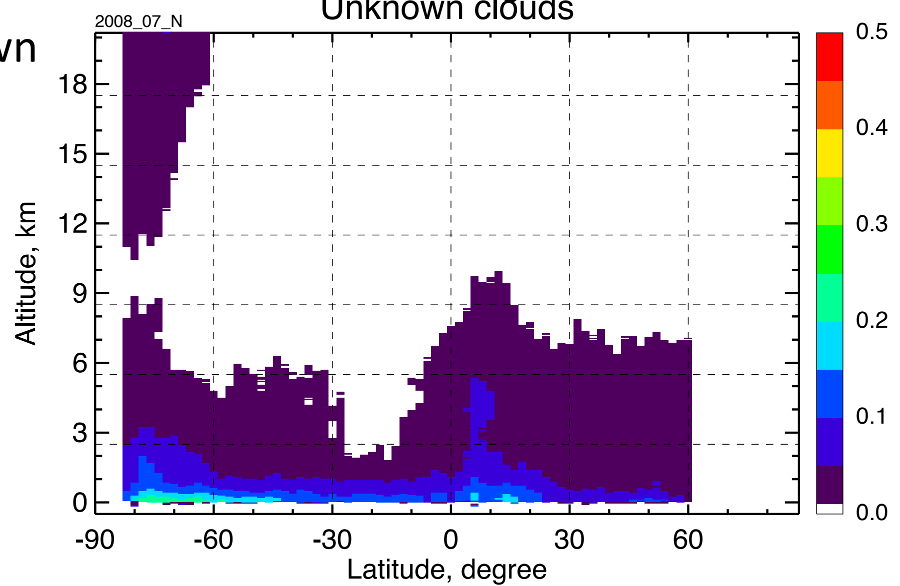
Ice cloud



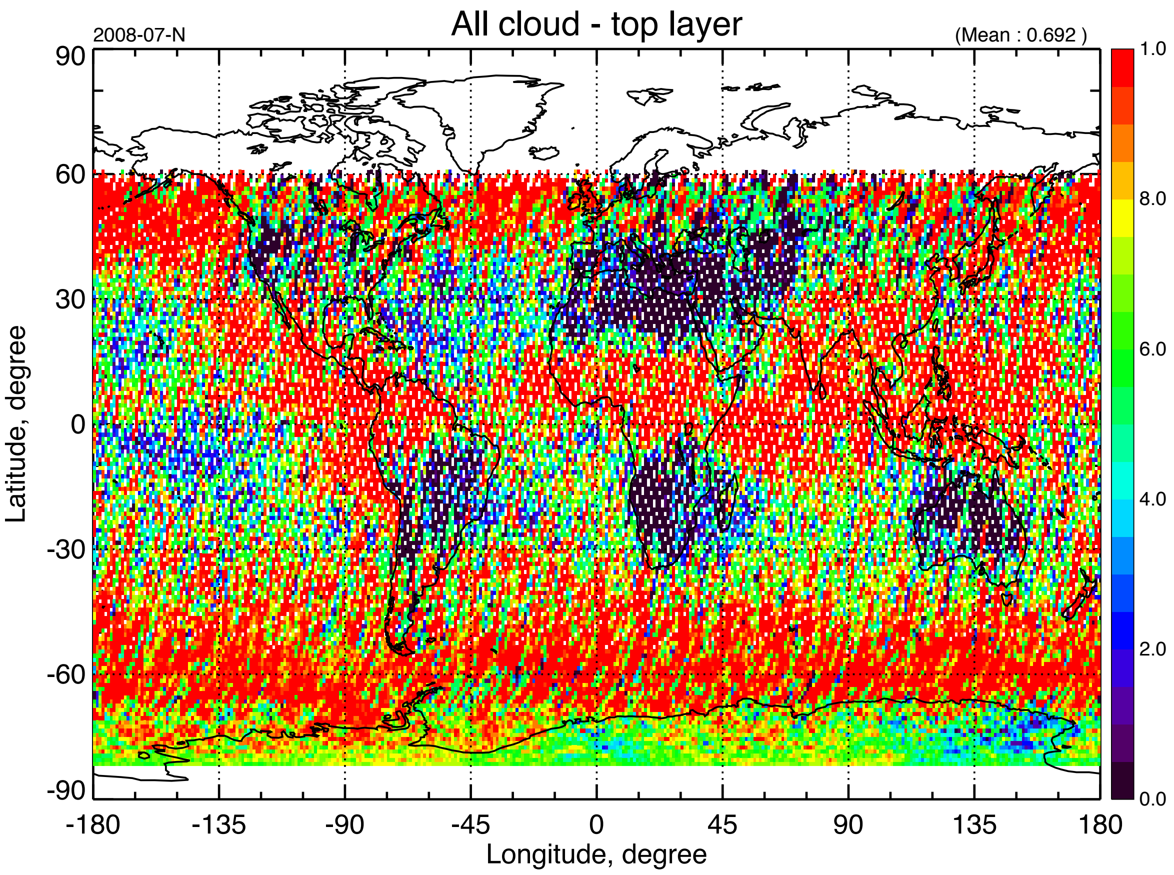
Water cloud



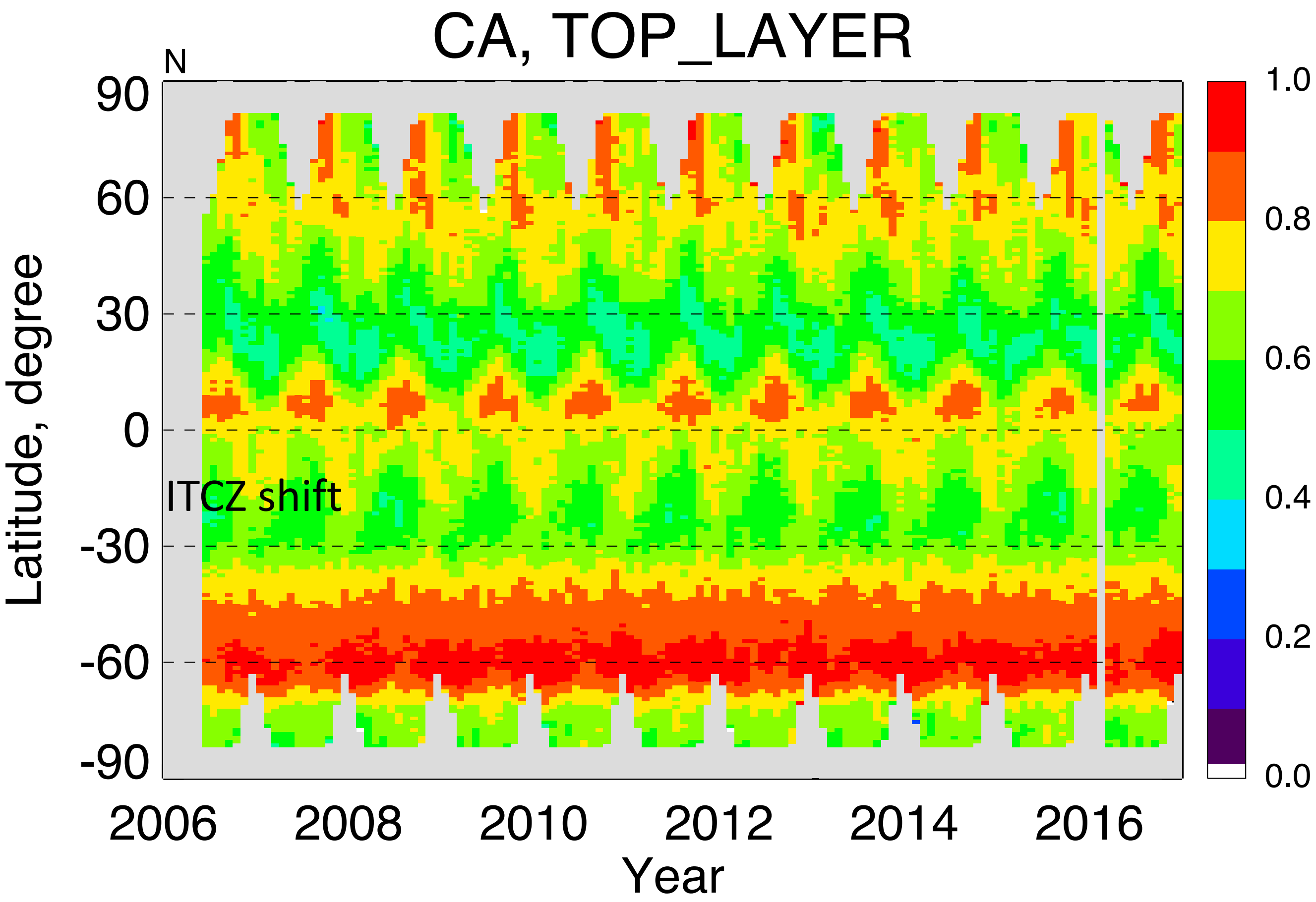
Unknown cloud



GEWEX cloud product



Night, July 2007



Night, Jun 2006 – Dec 2016

Microwave Barometric Radar and Sounder

Pressure – The Missing Retrieval

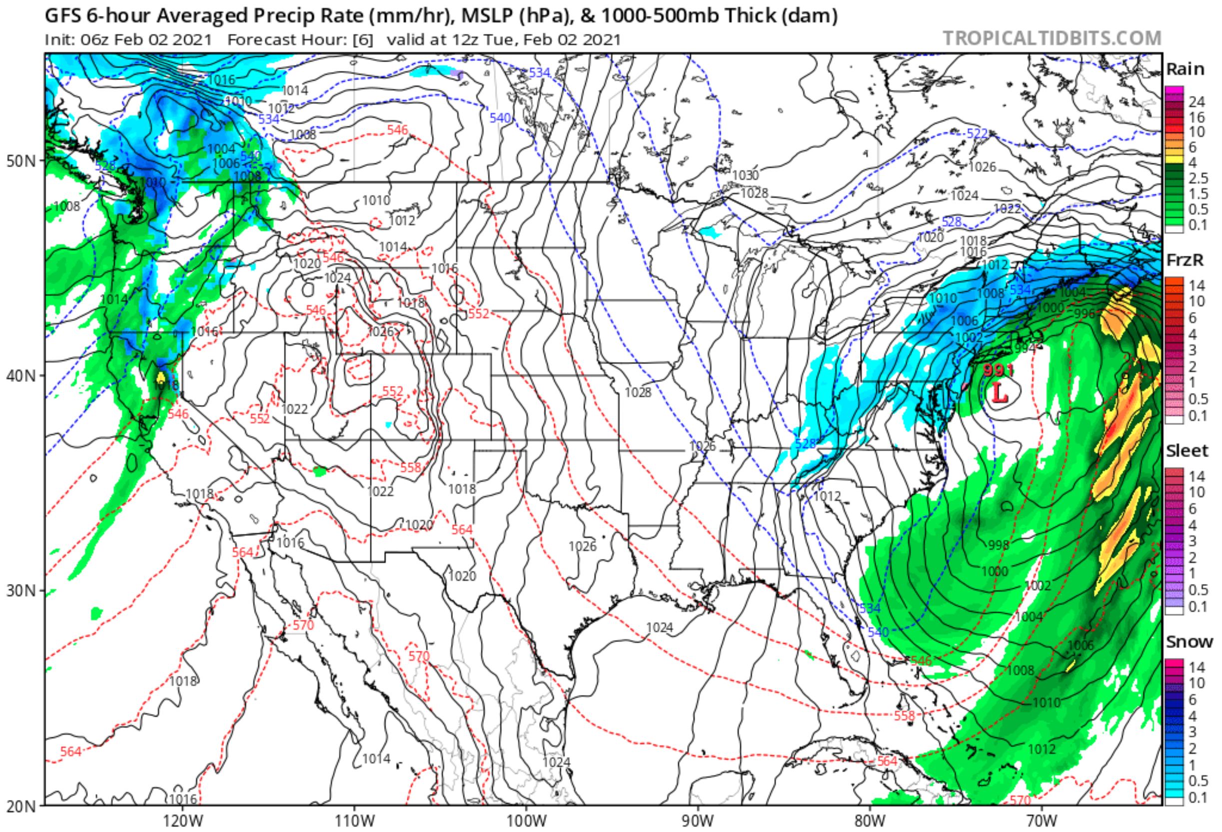
Pressure drives atmospheric motion.

$$\frac{d\mathbf{V}}{dt} = \mathbf{P}_n + \mathbf{C} + \mathbf{F}$$

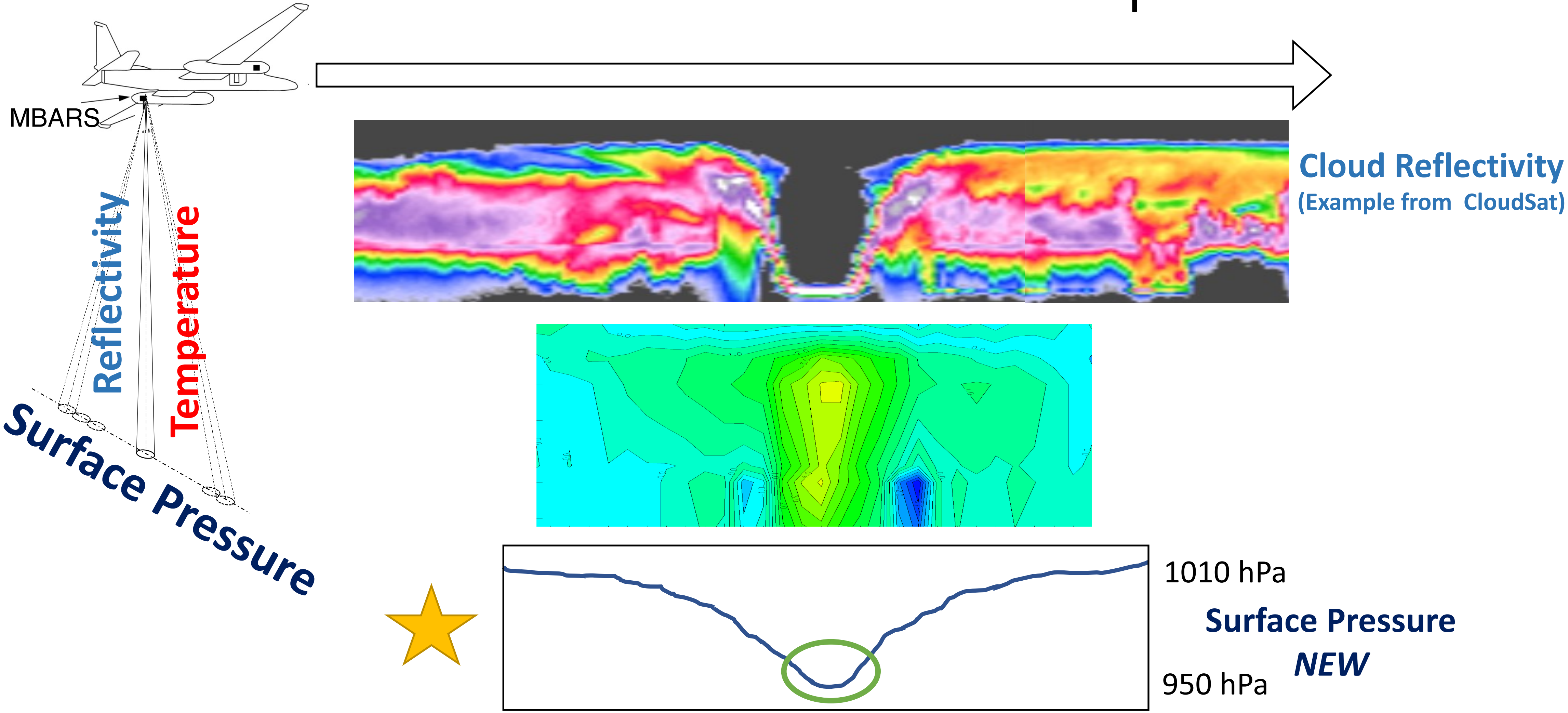
Horizontal atmospheric acceleration is from the sum of the **pressure gradient,** Coriolis, and frictional forces.

Measurement of pressure gradients allows retrievals of **horizontal winds.**

Tropical and subtropical **cyclones** are defined by the *location* and *strength* of the associated low-pressure anomaly.



Instrument Concept



Airborne flight demonstration of a V-band differential absorption radar, and evaluation of algorithms and sensitivity to atmospheric pressure.

Observational Approach

- Oxygen amount measurements:
  frequency selected -- 70.0, 67.75, 65.5 GHz
  linear water absorption & surface reflection

- Surface air pressure obtained from the barometric radar of MBARS + column water amount

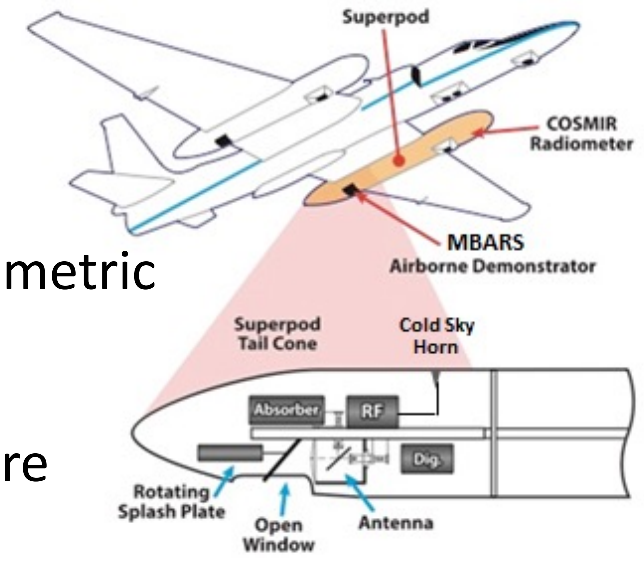
- Air temperature profile from the temperature sounder of MBARS

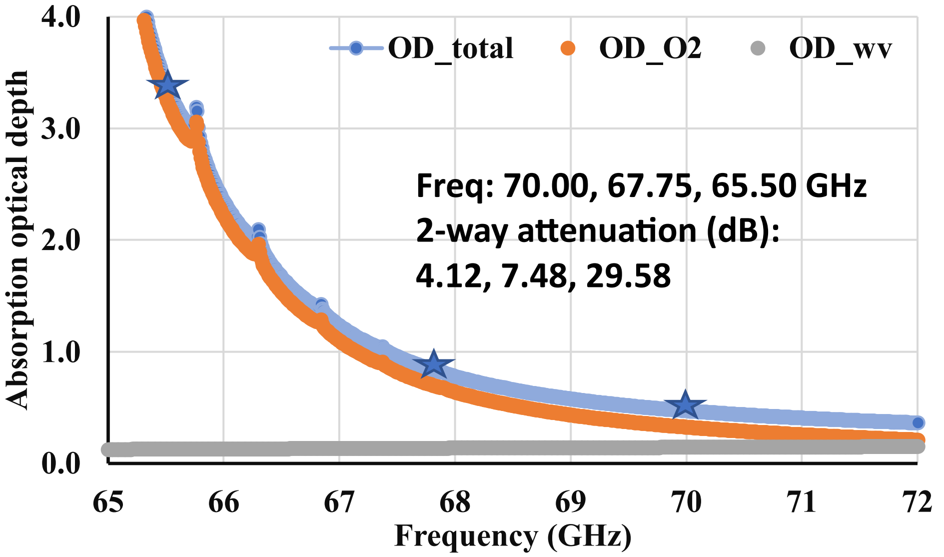
- Pressure profiling: hypsometric equation

$$Z_2 - Z_1 = \frac{R_d \overline{T_v}}{g_o} \ln\left(\frac{P_1}{P_2}\right),$$

where $\overline{T_v}$ is a virtual temperature. Z, g_o and R_d are geopotential height, acceleration of gravity, and dry air gas constant, respectively.

- Radar ranging capability for land/sea ice areas

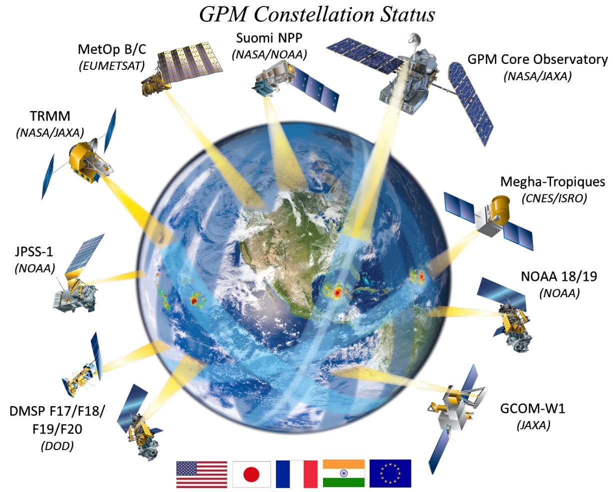




Climate extremes become new normal

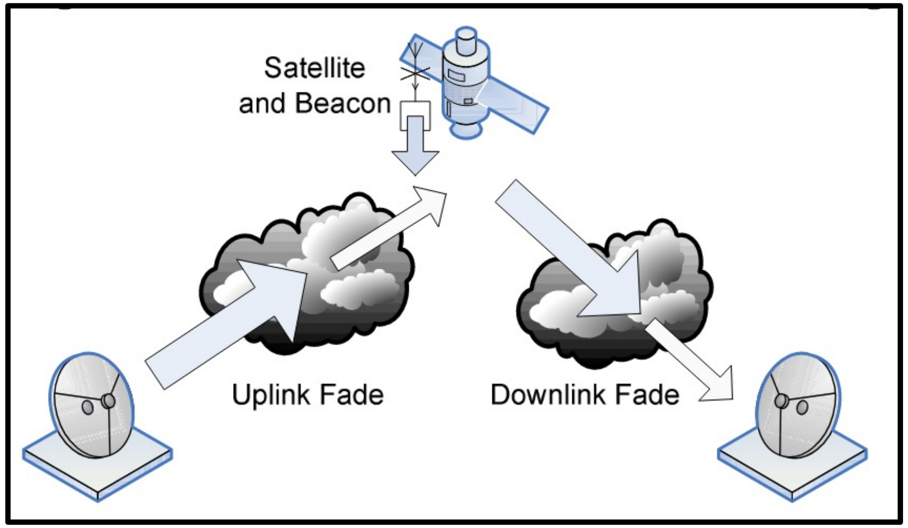
- The “dry gets drier and wet gets wetter” (DDWW) paradigm → an urgency to better monitor water content in the atmosphere.

- Current orbital/suborbital observations of Designated Observables (DOs) of atmospheric water are complex, high cost, limited spatiotemporal resolution



Next generation signals-of-opportunity (SoOp)

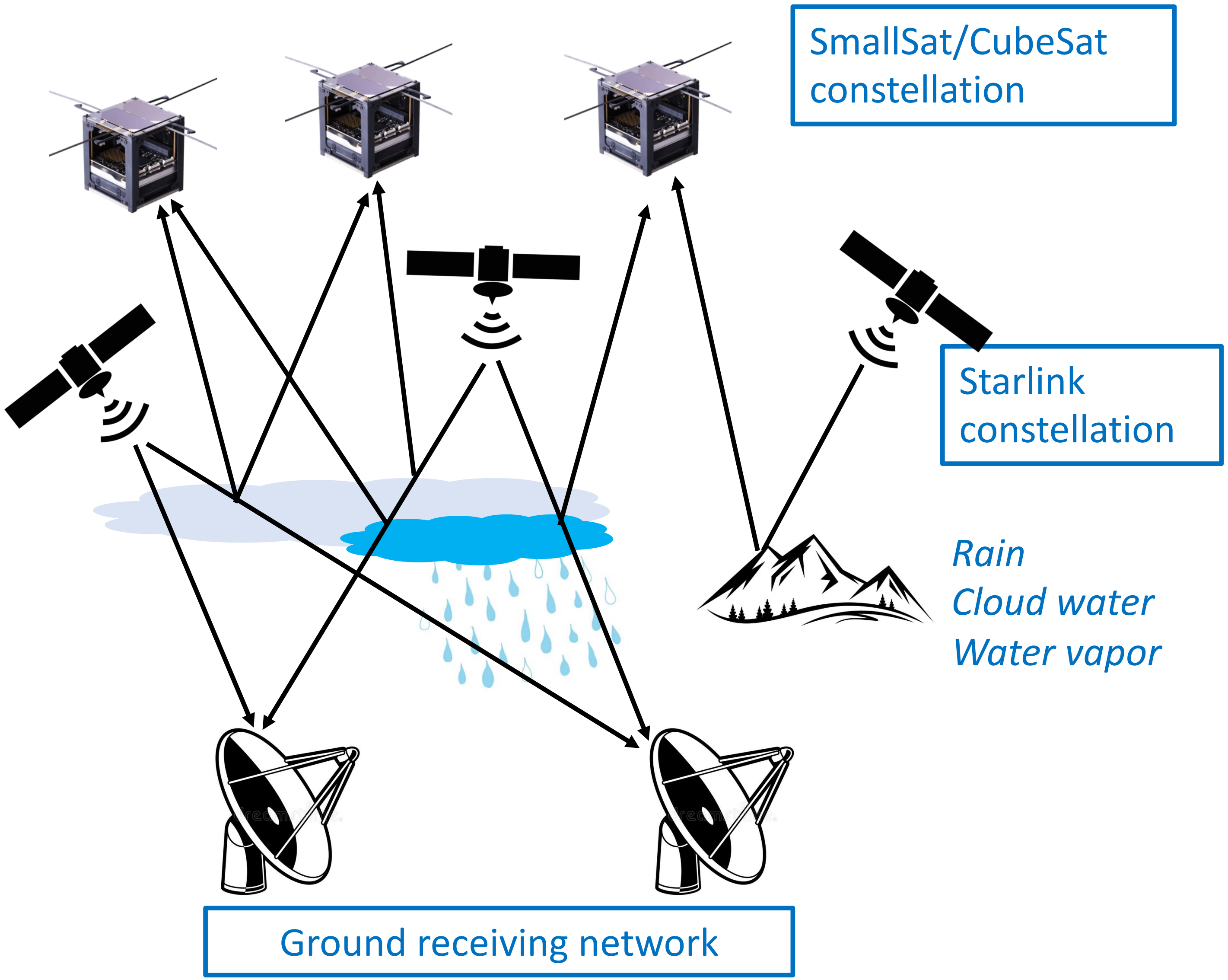
Rain fading



Saam [2010], *Protocols for rain fade mitigation using simultaneous X/Ka communications*, IEEE

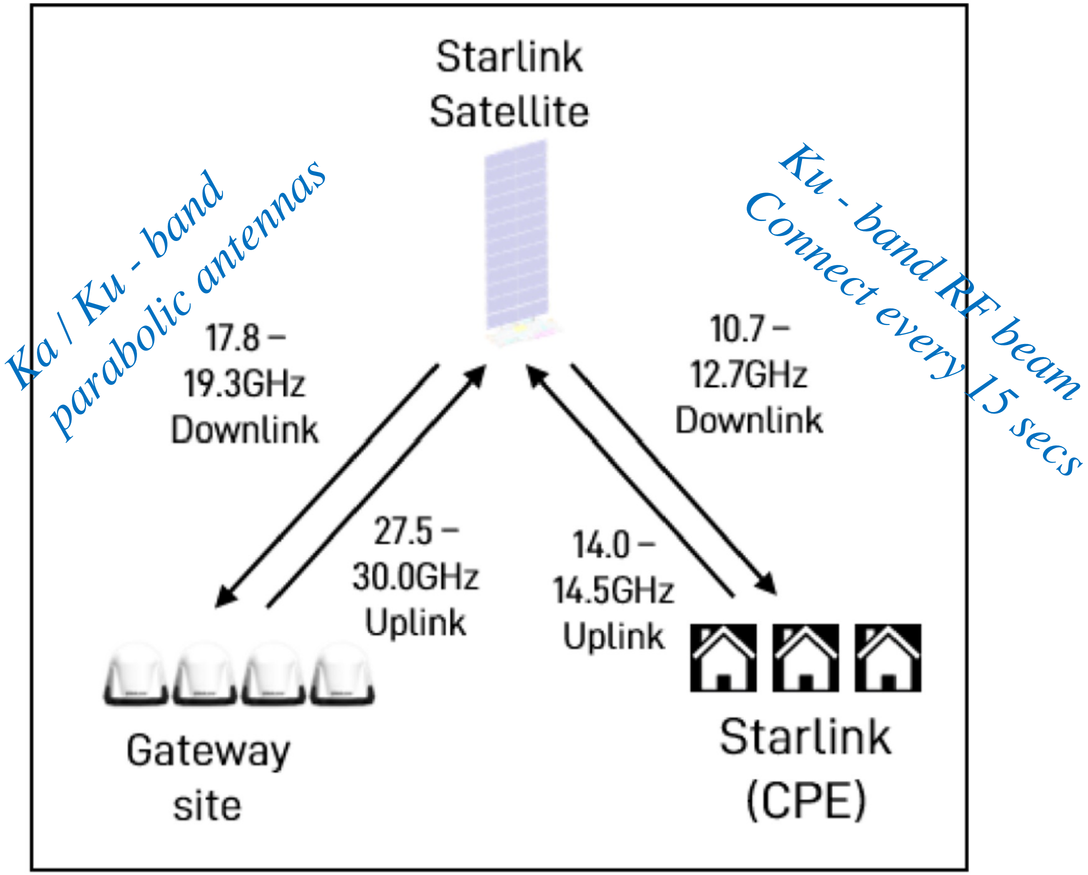
- Affect communication – ”trash”
- Contain atmosphere water information – “treasure”

Mission concept



Starlink constellation

Figure 1 - Starlink Network Architecture



- ❑ Provide low latency, broadband internet system to rural area.
- ❑ As of 3 March 2023, total launched satellites are 4053. 3711 are working and 3197 are operational.

Science applications of Starlink

Strength: perfect band frequencies; multiple bands; extremely high spatiotemporal resolution due to dense network; global coverage…

Atmosphere application

- ❑ Ka detects light precipitation; Ku/Ka observe heavy rain in the tropics and light rain and snow in high altitudes, and hydrometeor drop size distribution
- ❑ *E.g.*, precipitation radars on NASA/JAXA TRMM (Ku-band, 13.8 GHz) and GPM (Ku/Ka band, 13.6 GHz/35.5GHz)

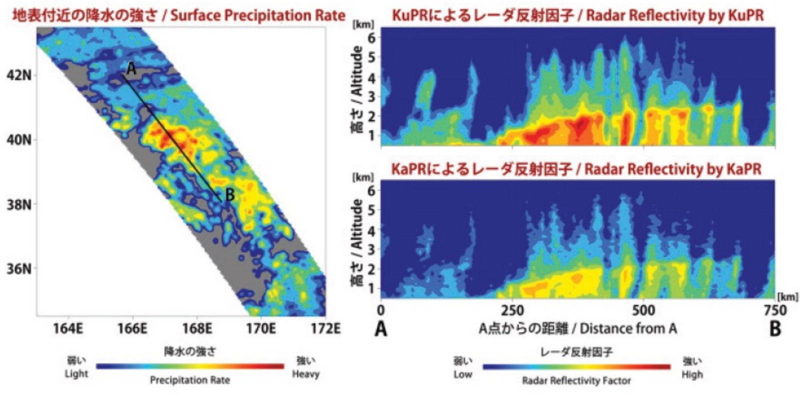


FIGURE 2.11 Examples of DPR 3D imagery for a hurricane. SOURCE: JAXA/NASA.

Land surface application

- ❑ Sea ice thickness possible with Ka/Ku dual bands, assuming high accuracy of timing
- ❑ *E.g.,* Ku-band altimeter onboard ESA CyroSat-2 satellite.

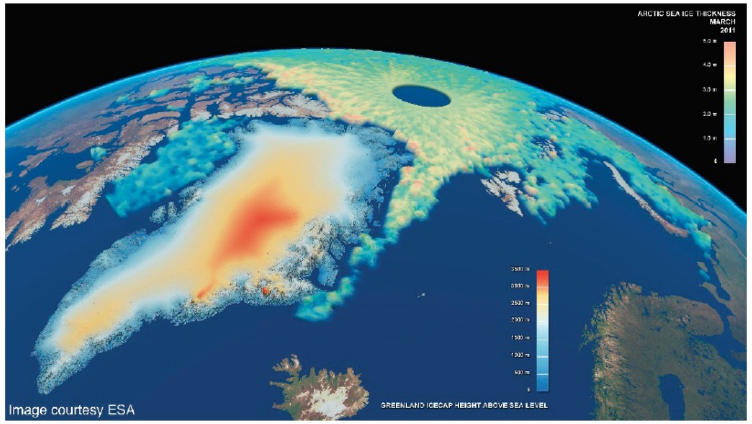


FIGURE 4.6 This map shows Arctic sea ice thickness, as well as the elevation of the Greenland ice sheet, for March 2011. The data come from the European Space Agency CryoSat-2 satellite utilizing a K_u-band altimeter. For the sea ice, green shades indicate thinner ice, while the yellows and oranges indicate thicker ice. SOURCE: Courtesy of Planetary Visions/CPOM/UCL/ESA.

Goal/Objective

Goal: Develop next generation capability of atmospheric water content observations with high spatiotemporal sampling, which will greatly improve weather and climate studies beyond the state-of-the-art.

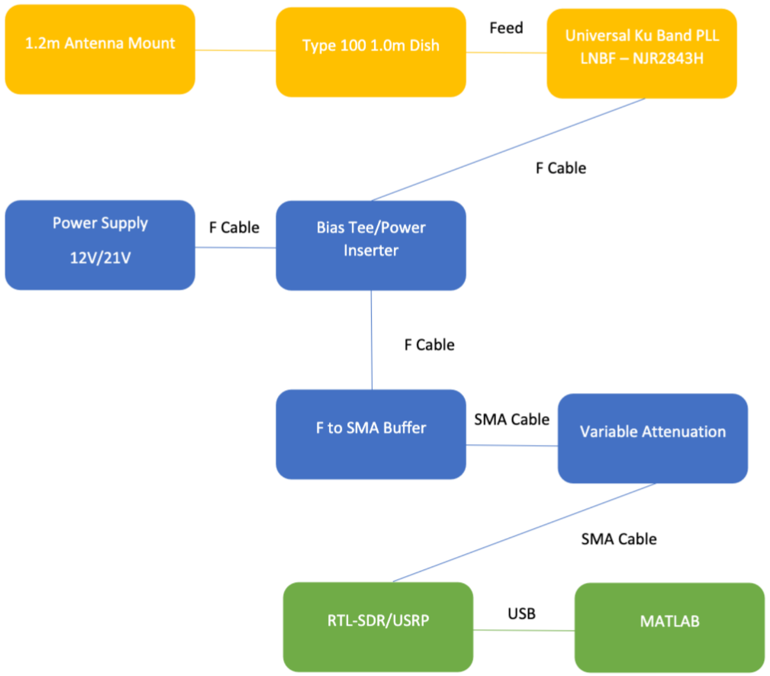
Objective: mission concept of multistatic Small Sat constellations and ground networks for atmospheric water observations

Milestones and schedule

- Year 1: build a ground receiving system; develop a retrieving algorithm (completed in FY22)
- Year 2: test and calibrate the system; algorithm improvement (funded for FY23)
- Year 3: validation; proof of concept; mission concept development (projected for FY24)

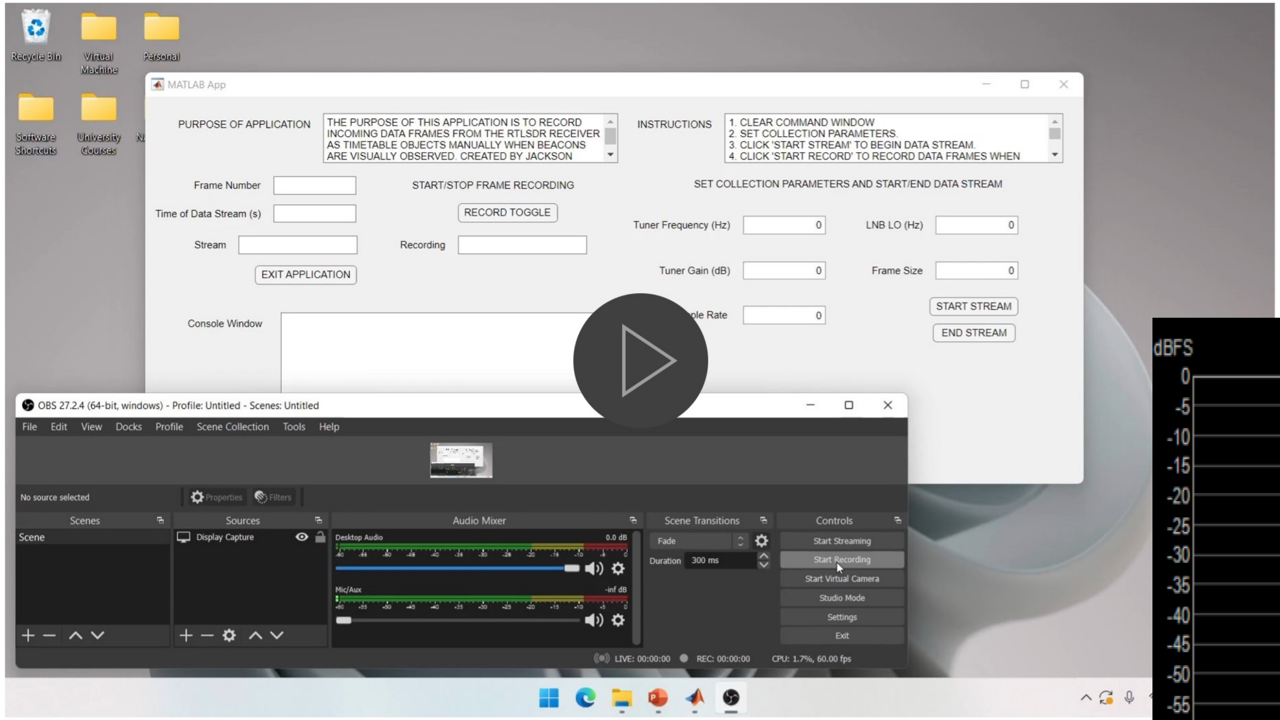
System Design

Ground Station Wiring and Components

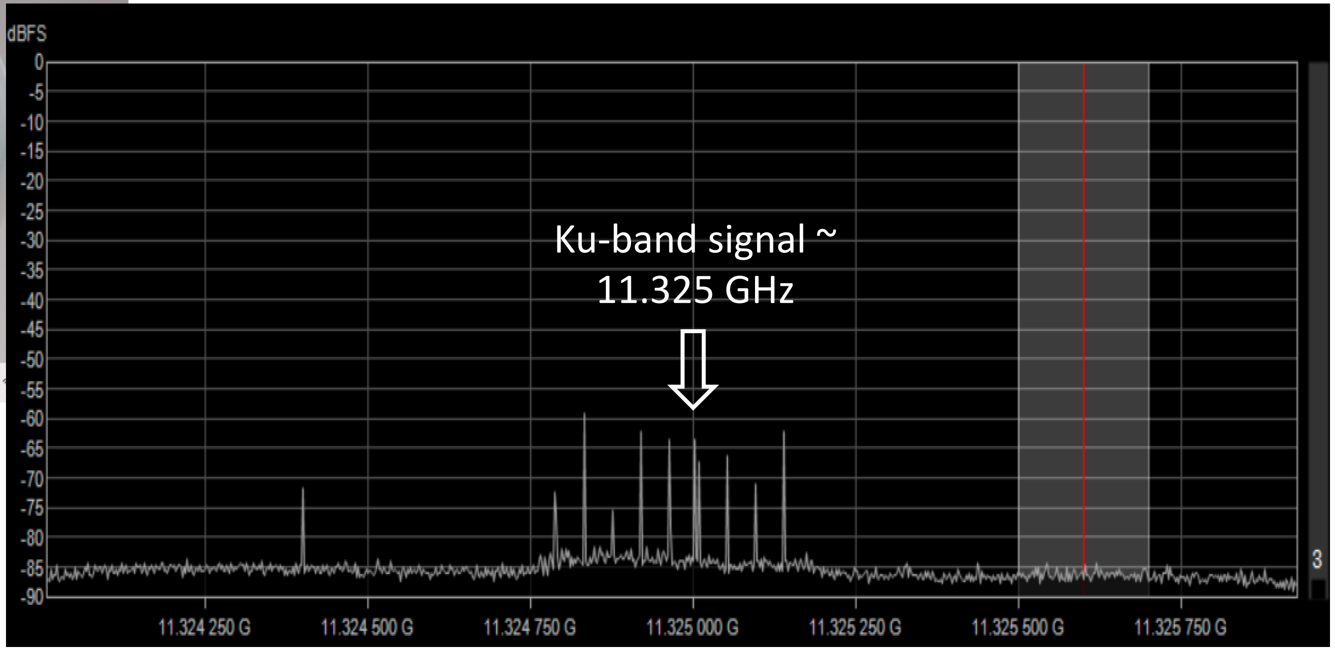


Ground receiving system in Maine

Data recorded with MATLAB + Simulink

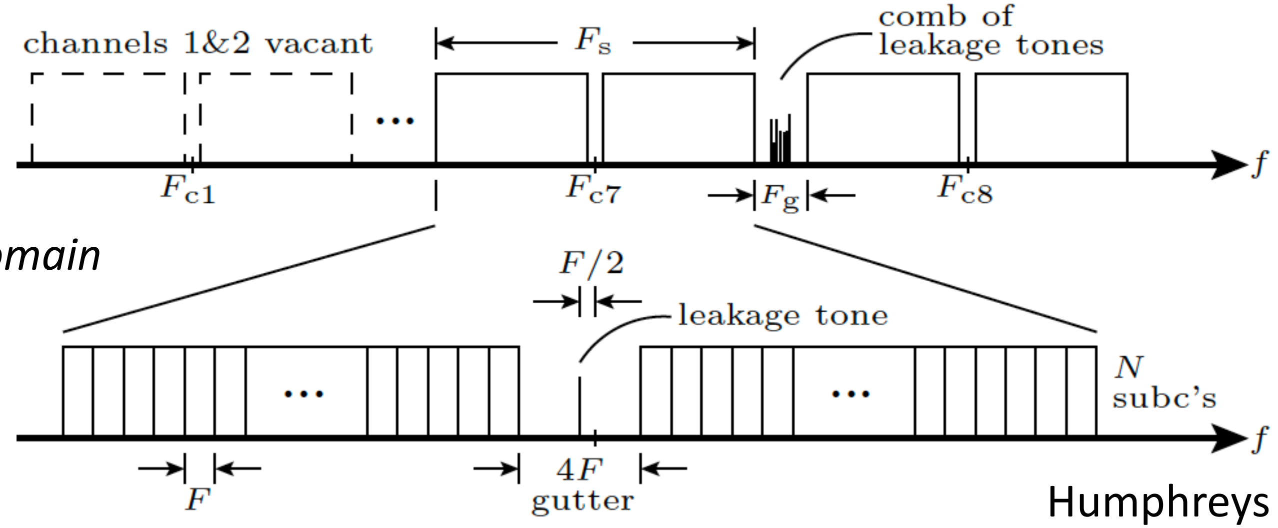


Received Starlink signals



Orthogonal frequency division multiplexing (OFDM)

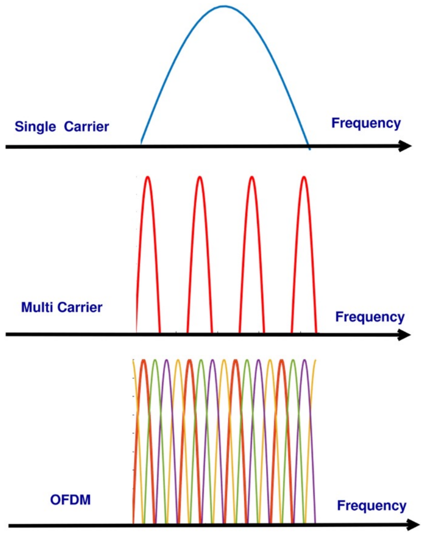
In frequency domain



Humphreys et al. [2022]

Fig. 5: Channel layout for the Ku-band Starlink downlink.

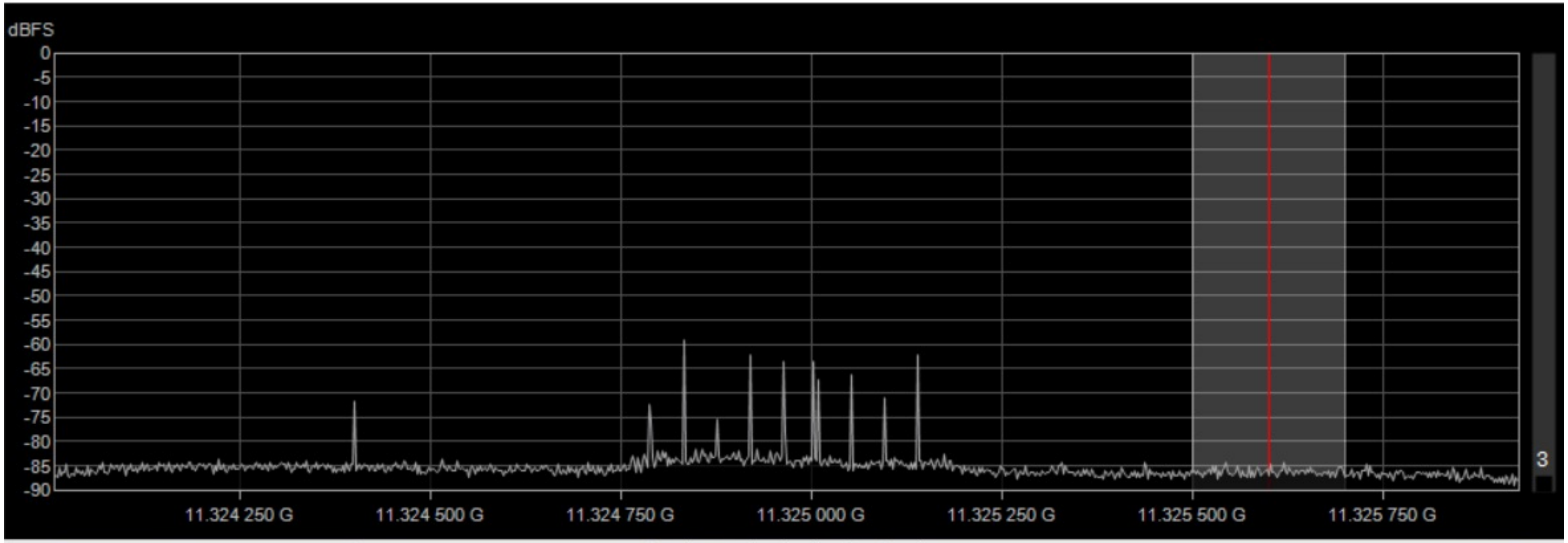
Same method used in digital radio, digital TV, Wi-Fi, cellular LTE/4G/5G



- 8 channels, each with a bandwidth of F_s = 240 MHz, guard band F_g = 10 MHz
- Only one channel appears to be active at a time within a service cell
- The lower two channels are currently vacant → avoid interfering with the 10.6-10.7 GHz radio astronomy band
- Each channel's central four subcarriers are vacant, leaving a mid-channel gutter

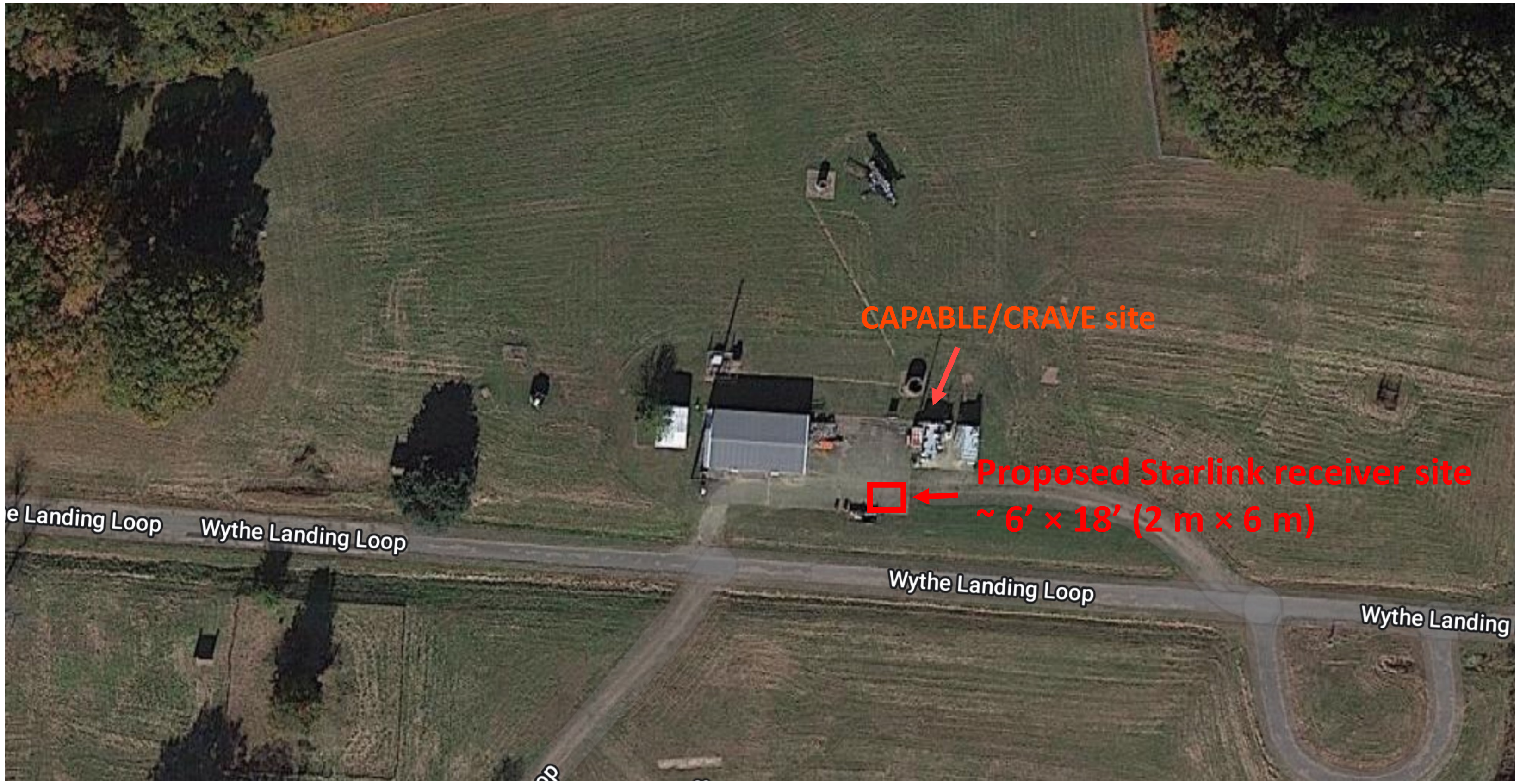
The Maine system recorded Ch3

Channel	Ch1	Ch2	Ch3	Ch4	Ch5	Ch6	Ch7	Ch8
f range GHz	10.70-10.95	10.95-11.20	11.20-11.45	11.45-11.70	11.70-11.95	11.95-12.20	12.20-12.45	12.45-12.70
$F_{midpoint}$ GHz	10.825	11.075	11.325	11.575	11.825	12.075	12.325	12.575
F_{ci} GHz			11.325 + 0.000117					

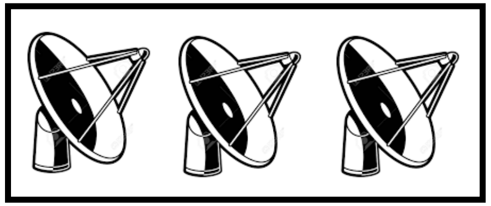


Proposed two more receiving systems at LaRC:

~ 6 feet × 18 feet (2 m × 6 m) at the southeast corner of parking lot



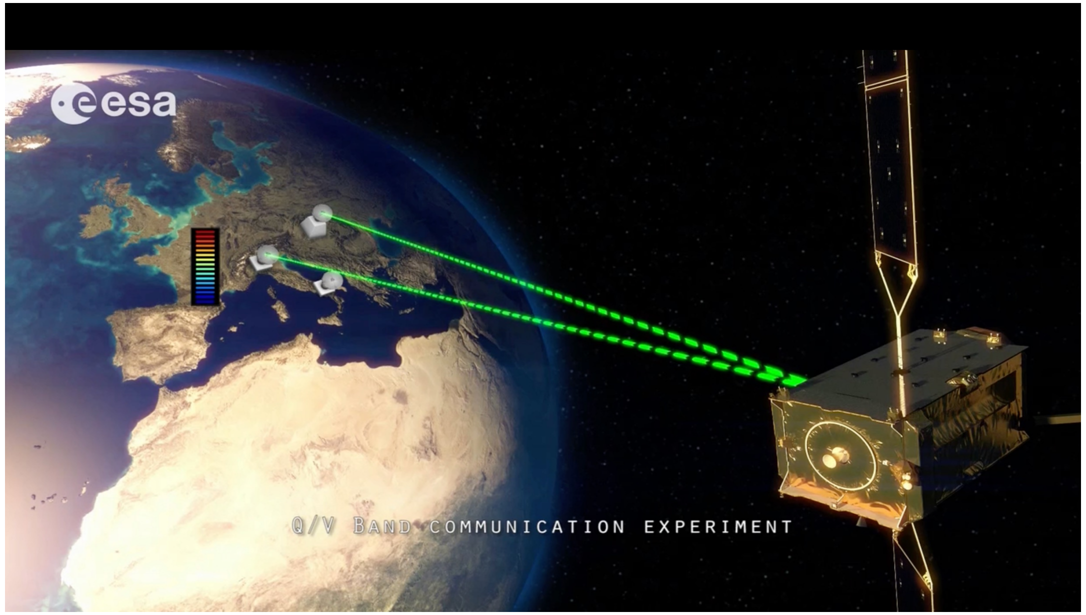
Proposed configuration:
Three systems

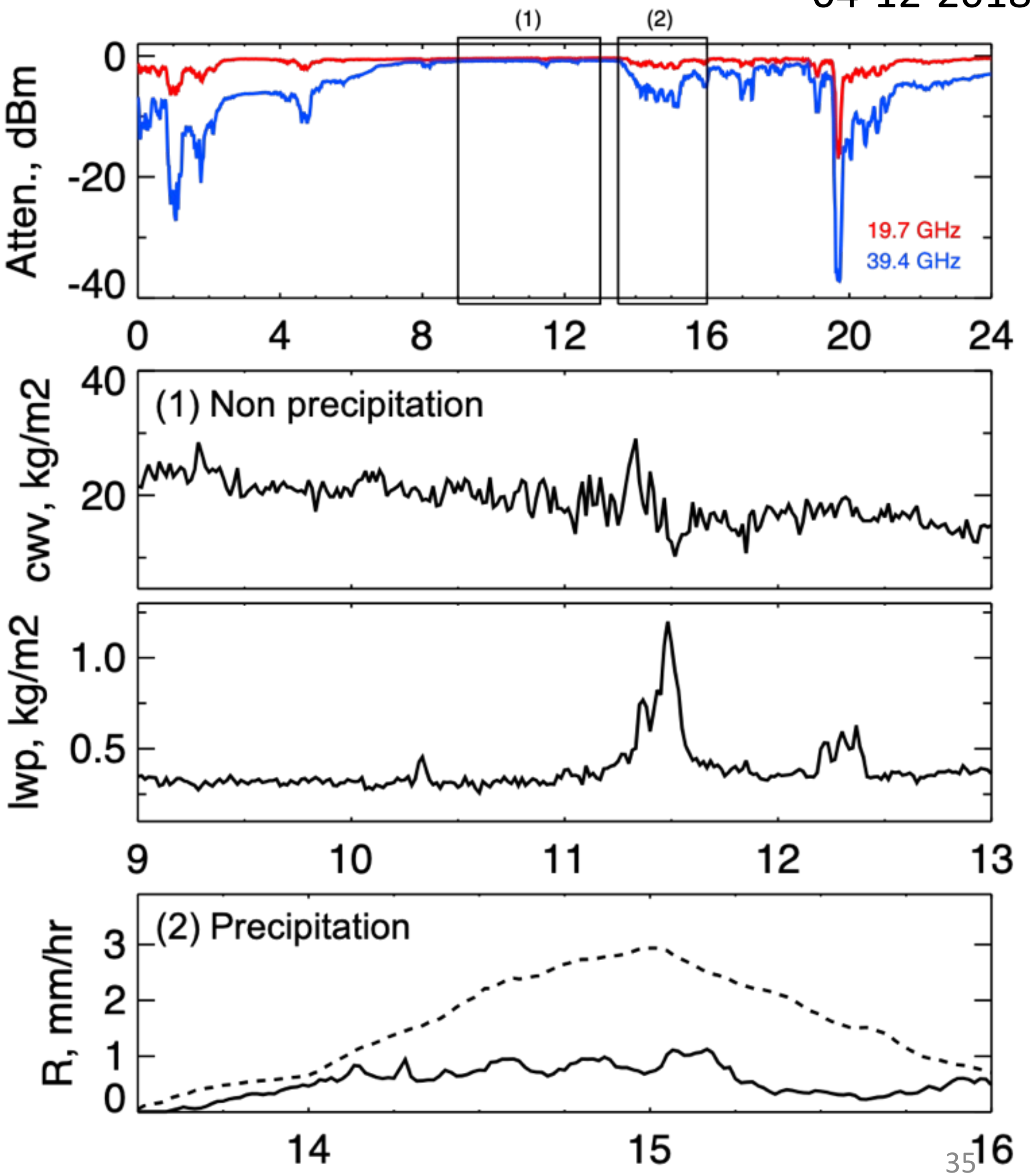


Algorithm development

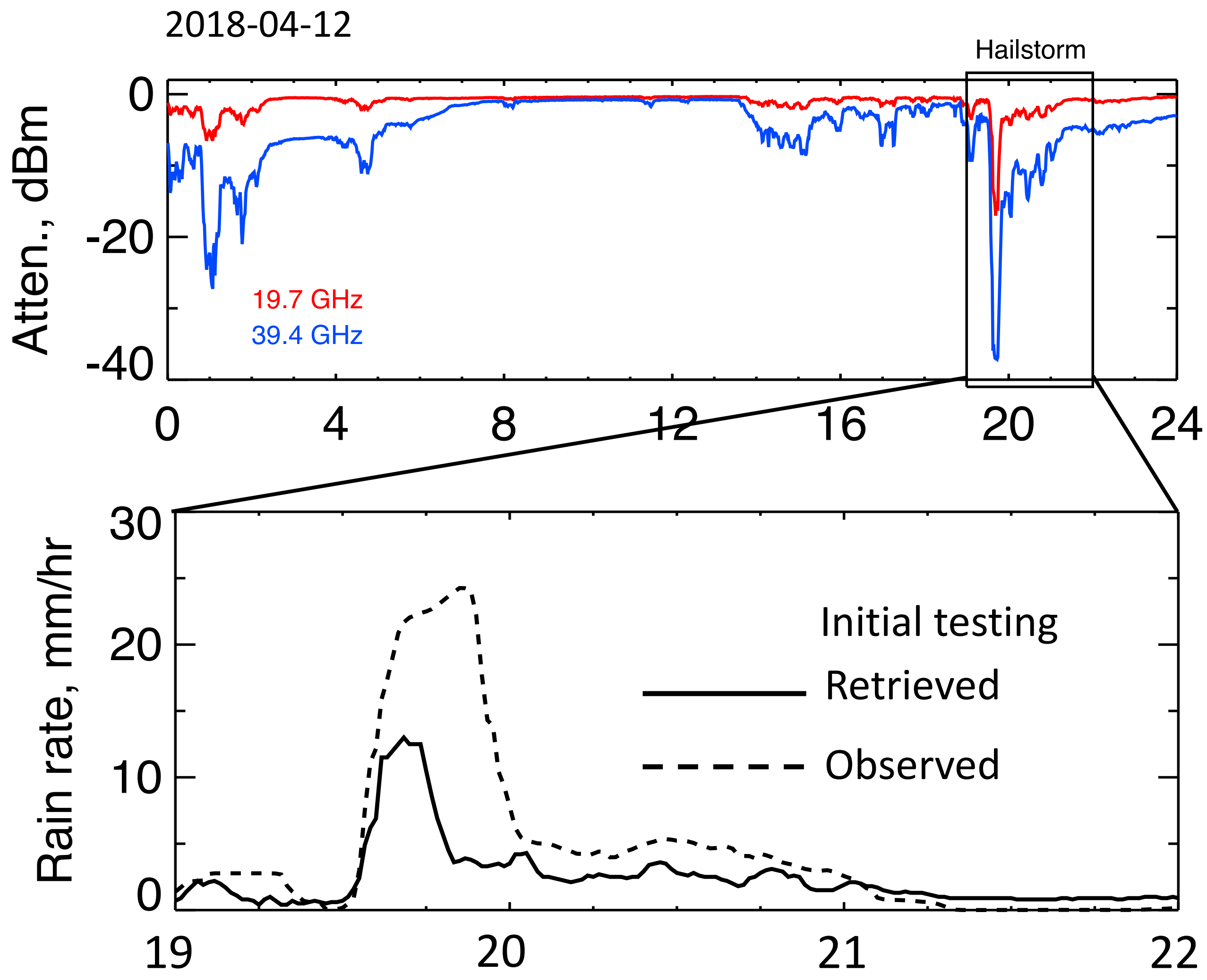
04-12-2018

- Tested with the beacon signals from ESA telecom satellite *AlphaSat*.
- Non-precipitation (1): retrieved column water vapor and liquid water path in cloud
- Weak precipitation (2): retrieved rain rate





- Retrieve rain rate during a heavy precipitation event (hailstorm)
- Considered strong Mie scattering of ice hailstones. The Mie scattering code is from the NASA GISS.
- Enhancements: added porous ice model; considered small precipitation cell and slant path
- The retrieved rain rate is within 20% of in-situ disdrometer measurements.



Where to go from here?

- CALIPSO enters closing phase
  - Continue science support for final release
- MBARS retrieval
  - Science analysis and algorithm development
- Starlink project
  - Continue lead the demonstration efforts
  - Funding opportunity: FY24 IRAD → NASA ESTO In-Space Validation of Earth Science Technologies Program → Small/CubeSat constellation opportunity

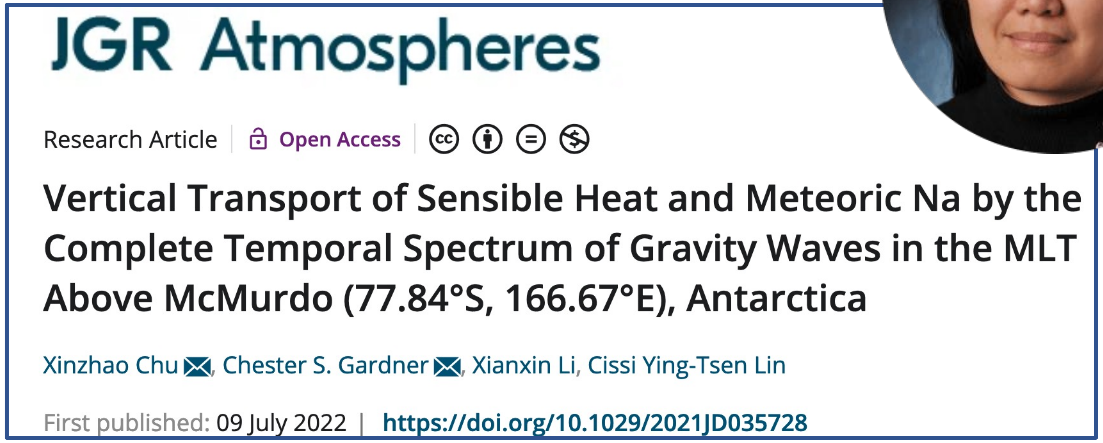
3. Interdisciplinary between space and terrestrial weather

- **Impact of space weather to terrestrial weather?**
  - Solar irradiance seems constant, ~ 1370 watt/m^2, variation < 0.1%.
  - Radio and X bands?
  - Solar energetic particles? Galactic cosmic Ray?

- How **space weather contribute to CALIPSO low energy shot issue** over the South Atlantic Anomaly?

- **Extend ground atmosphere lidar capability for space and beyond**?

Na Doppler and Fe Boltzmann lidars at Antarctic



JGR Atmospheres

Research Article | Open Access

Vertical Transport of Sensible Heat and Meteoric Na by the Complete Temporal Spectrum of Gravity Waves in the MLT Above McMurdo (77.84°S, 166.67°E), Antarctica

Xinzhao Chu, Chester S. Gardner, Xianxin Li, Cissi Ying-Tsen Lin

First published: 09 July 2022 | https://doi.org/10.1029/2021JD035728

Thanks for listening!

Any questions? Comments? Concerns?